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**TURBULENT HEAT TRANSFER  
INVESTIGATION: TURBULENCE LENGTH  
SCALES AND TURBINE HEAT TRANSFER**

**Jason Sharp  
Pete Harris**

**3 MAY 1996**

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RICHARD B. RIVIR  
Manager, Aerothermal Research  
Turbine Branch  
Turbine Engine Division  
Aero Propulsion & Power Directorate



CHARLES D. MACARTHUR  
Chief  
Turbine Branch  
Turbine Engine Division  
Aero Propulsion & Power Directorate



RICHARD J. HILL  
Chief of Technology  
Turbine Engine Division  
Aero Propulsion & Power Directorate

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**Nomenclature List**

$B_1$	- air inlet angle, degrees
$B_2$	- air exit angle, degrees
$B_x$	- axial chord length, in
$C$	- degrees Celsius
$e$	- voltage
$e_0$	- zero velocity voltage
$h$	- heat transfer coefficient, $W/m^2K$
$Hz$	- Hertz
$I$	- electric current, amps
in	- inches
$K$	- degrees Kelvin
$k_{air}$	- thermal coefficient for air, $W/mK$
kg	- kilogram
$l$	- length of gold sheet, in
$m$	- meters
$N$	- Newton, $kg\ m/s^2$
$Nu$	- Nusselt number
Ohm	- measure of resistance
Ohm/SQ	- resistance per square
$p$	- pitch distance between turbine blades, in
$P_\infty$	- atmospheric pressure, psi
psi	- pounds per square inch
$q''$	- heat transfer flux, $W/m^2$
$q_c''$	- convective heat transfer flux, $W/m^2$
$q_L''$	- conductive heat transfer flux, $W/m_2$
$R(T)$	- autocorrelation function
$R_{35.7''}$	- resistance per square of gold at $35.7^\circ\ C$ , Ohm/SQ
$Re$	- Reynolds number
$s$	- seconds
$S$	- surface arc length, in
$St$	- Stanton number
$T_\infty$	- free-stream air temperature
$T_{LC}$	- surface temperature of yellow liquid crystal band, $C$
torr	- pressure measurement also mm Hg
$T_u$	- longitudinal turbulence intensity (See Equation ?)
$u$	- local velocity fluctuation
$U$	- local velocity, $m/s$
$W$	- Watts
$w$	- width of gold film, in
$x, y, z$	- longitudinal, lateral, vertical axis/distances, in
$\rho$	- density, $kg/m^3$
$\epsilon$	- emmissivity
$\sigma$	- Stefan-Boltzman constant, $W/m^2K^4$
$\mu$	- viscosity of air, $Ns/m^2$

$\Delta P$	- dynamic pressure, torr
$\Lambda_u$	- macro or integral turbulent length scale, m
$\lambda_u$	- microscale turbulent length scale, m
$\delta_x$	- experimental uncertainty in parameter x

## **Introduction**

### **Theoretical Background**

The heat transfer on turbine blades directly affects the way engine designers can develop new turbines to allow for higher turbine inlet temperatures in engines. A better understanding of turbine blade heat transfer allows for better and more efficient cooling techniques to be developed. With more efficient cooling, increases in the turbine inlet temperature can be made without advances in materials technology. Since this has a direct and beneficial effect on the engine cycle design, reflected in greater specific thrust and lower thrust specific fuel consumption, this area is of great interest to the gas turbine engine industry. If a greater understanding of the heat transfer on such blades can be reached, new and better designs can be made.

The effect of turbulence on heat transfer has been known for some time but has yet to be physically modeled with great success. There are several parameters to describe the turbulent flow that are used in this study. The first of which is turbulence intensity. Turbulence intensity in the axial direction, noted as  $T_u$ , is one of the parameters of interest in this investigation. Turbulence intensity is a method of measuring non-dimensional turbulence in a single direction. It is the fluctuating velocity expressed as a percentage of the non-fluctuating velocity. This is expressed as:

$$T_u = \frac{\sqrt{u^2}}{U} \quad [1]$$

Roach developed correlations for predicting turbulence intensity generated by passive grids (Roach 82-92). For a square mesh of square grids this correlation is Reynolds number independent. This correlation is given as:

$$T_u = C \left( \frac{x}{d} \right)^{-5/7} \quad [2]$$

is a correlation constant which for square mesh of square bars is 1.13,  $d$  is the distance or bar diameter, and  $x$  is the distance downstream of the grid (Roach 84-). This equation allows for the prediction of turbulence intensity or for this study the distance to achieve a desired turbulence intensity.

Parameters of interest are the micro and macro or integral length scales. The micro scale is the dissipation scale. It may be considered a measure of the average length scale at which are primarily the method in which turbulence energy is dissipated (Roach 85). The macro scale is described by the equation:

$$\frac{1}{\lambda_u} = \frac{-1}{2U} \left\{ \frac{\partial^2 R(T)}{\partial T^2} \right\}_{T=0} \quad (\text{Roach, 85}) [3]$$

$R(T)$  represents the autocorrelation function, a correlation of each point to all points at time  $T$ . The second derivative of this correlation is used to determine the response of this function.

The macro length or macro scale may be considered to be a measure of the largest eddy in the flow field (Roach, 85). This is found by determining the area under the autocorrelation curve as it goes from 1 to 0. This area is determined by integrating this curve as the macro length scale is defined as:

$$\Lambda_u = U \int_0^{\infty} R(T) dT \quad [4]$$

The determination of the free stream velocity by the pitot probe is done via the Bernoulli equation.

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The heat transfer coefficients are of direct interest to this investigation. For this study the blade will be heated by resistance heating to provide a surface temperature higher than the surrounding air temperature. This temperature difference will in turn drive convective heat transfer to occur. The amount of resistance heating can be calculated as follows:

$$\dot{q} = \frac{I^2 R_{35.7}''}{w^2} \quad [6]$$

In this equation  $\dot{q}$  is the heat transfer from the blade,  $I$  is the current applied to the blade,  $R_{35.7}''$  is the resistance per square of the gold, and  $w$  is the width of the gold layer. This represents the total heat transfer from the blade. In order to determine the convective heat transfer which is the target of this investigation the conductive and radiative modes of heat transfer must be accounted for. Since, the construction of the turbine blade is designed to minimize conduction by using a highly insulative closed-cell foam core, that mode is assumed to be negligible. The radiative mode is calculated by the following equation:

$$\dot{q}_R = \varepsilon \sigma (T_{LC}^4 - T_{\infty}^4) \quad [7]$$

where  $T$  is the absolute temperature in Kelvin for both cases. By subtracting these modes from the total heat transfer the conductive heat transfer can be determined.

$$\dot{q}_c = \dot{q} - \varepsilon \sigma (T_{LC}^4 - T_{\infty}^4) - \dot{q}_L \quad [8]$$

Once the conductive heat flux is determined the conductive heat transfer coefficient can be determined as follows.

$$h = \frac{\dot{q}_c}{(T_{LC} - T_{\infty})} \quad [9]$$

The next step in the process is to non-dimensionalize this coefficient. This can be reduced to either the Stanton number or Nusselt number for reporting. These two are determined as follows:

$$St = \frac{h}{\rho V_{\infty} c_p} \quad [10]$$

$$Nu = \frac{h B_x}{k_{air}} \quad [11]$$

The Nusselt number can be divided further by the square root of Reynolds number to remove any Reynolds number dependency in laminar flow regions.

### Experimental Background

This investigation builds on work previously performed at both the United States Air Force Academy and the University of California at Davis. This work includes investigating the effects of turbulence intensity on heat transfer as well as mapping the turbulence generated by grids. Baughn et al investigated the effect of turbulence intensity in a simultaneous study at UC Davis and USAFA. Their results can be summarized as the turbulence intensity is increased from 1% to 10% the heat transfer level increases, the suction side boundary layer transition moves upstream and the spanwise variation on the pressure side disappears (Baughn, et al 12). Baughn et al also note that these results compare favorably to rotating tests performed. This helps address the concern that cascade tunnels do not address rotational effects (Baughn, et al 12).

The study of turbulent flow quality produced by grids conducted last semester by Duncan and Peterson confirmed that the work done by Roach held true for the Cascade Wind Tunnel. The results of that investigation concluded that the correlation given by Roach worked well for passive generation such as will be used in this investigation. It also noted that the use of a grid

passive generation such as will be used in this investigation. It also noted that the use of a grid perpendicular to the flow instead of parallel to the cascade had negligible effects on the turbulence generated (Duncan and Peterson 18-19). That research used a round bar generation grid and thus the correlation coefficient is Reynolds number dependent as shown in Roach (Roach 86). This research tests a square mesh of square bars which Roach found to be Reynolds number independent in the range of interest (Roach 87).

With the effect of turbulence intensity investigated by Baughn et al and the effectiveness of generating turbulence by grids established by Roach and confirmed for the USAFA tunnel by Duncan and Peterson, this investigation establishes a relationship between length scales and heat transfer. By using a turbulence intensity level of 10%, the results of this investigation can be compared to Baughn et al, to analyze the effects of length scales. The objective of this project is to determine if a relationship exists between turbulent heat transfer and micro and macro length scales. Heat transfer is tested at 10% turbulence intensity. Additionally, a clean tunnel test is performed for comparison. Length scale comparisons will allow for a better understanding of turbulent heat transfer. Length scale investigations will provide data for updating turbulent CFD codes to include length scale effects. The investigation also looks at passive turbulence generation, comparing the results to the correlations reported by Roach (Roach 82-92).

## **Experimental Methods**

### **Experiment Setup**

The experiment takes place in the USAF Academy Aeronautics Lab Cascade Wind Tunnel. The Cascade Wind Tunnel is designed to place a linear cascade of turbine blades in a flow which will simulate the flow over the normally rotating turbine blades. The turbines in the

turbine around the 3rd or 4th stage with Reynolds numbers around 80,000. The tunnel is a closed loop system with a heat exchanger to provide for temperature control. In the test section are seven test blades with the end walls simulating two more blade surfaces. This setup is shown in Figure 1. The blades in the test section very closely match the Langston geometry. This geometry can be seen in Langston et al, 1977 (Langston 23).

The test section has a test probe which traverses parallel to the blade plane. This probe contains a hot film sensor, pitot-static probe and a wedge probe, which is not used in this study. The pitot-static probe is connected to a pressure transducer which outputs to a torr meter as well as the IFA 100. The hot film anemometer outputs to the IFA 100 and HP 3852A. Additionally a K type thermocouple outputs to the IFA 100 allowing for temperature measurements. Data from the IFA 100 and HP 3852A are input to the P90 computer which is controlled by TV3 software, which was written in the Aero Department. This setup is designed to collect the flow data. This can be seen in Figure 2 and Figure 3.



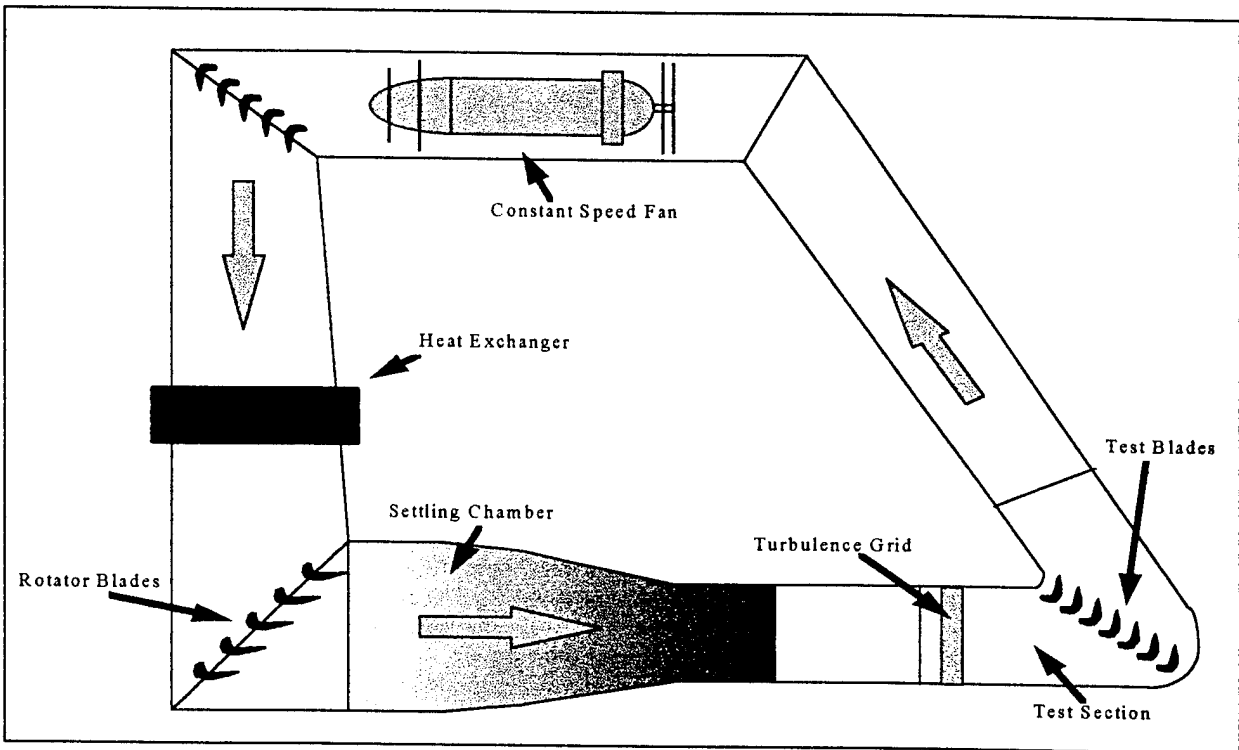


Figure 2: Cascade Wind Tunnel Schematic

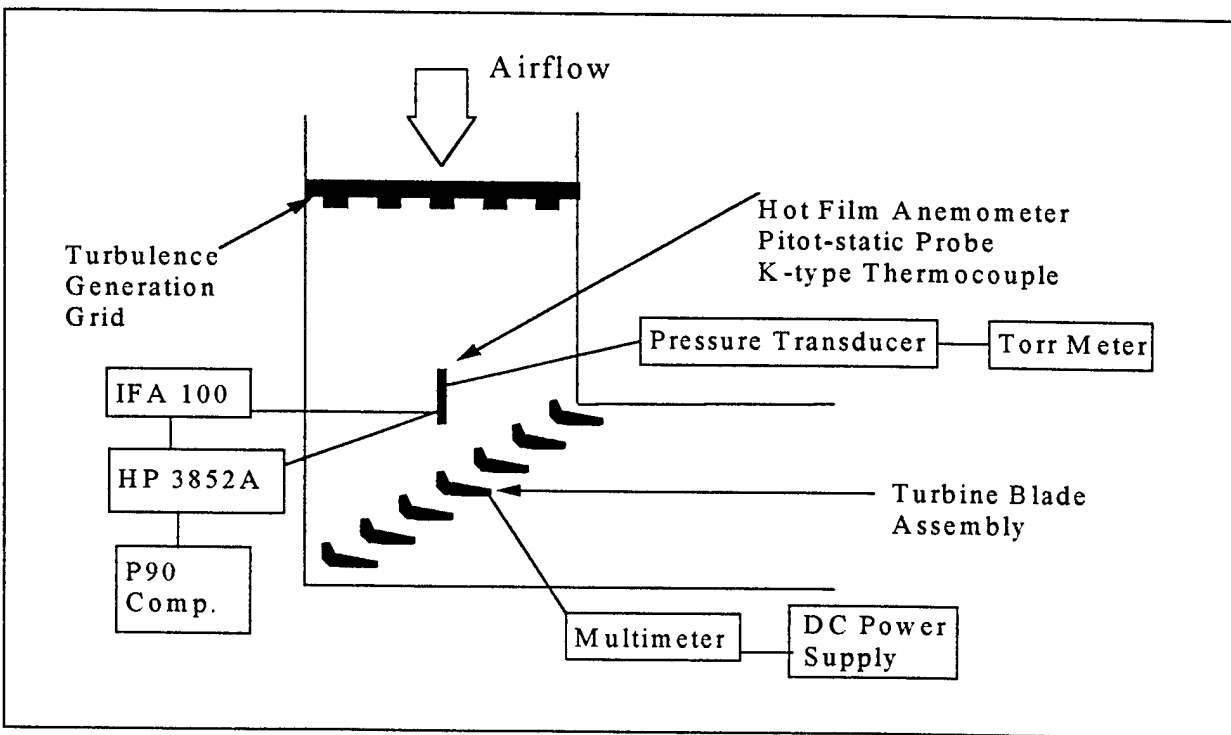
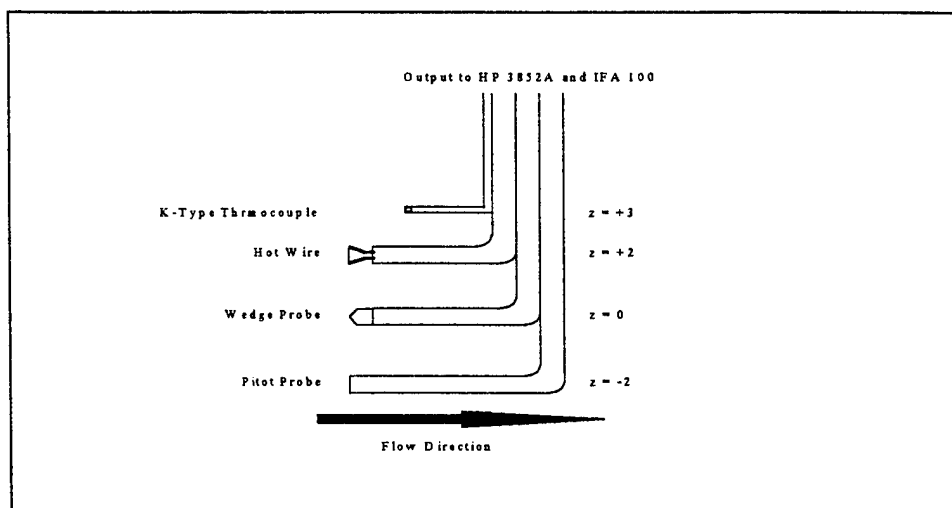
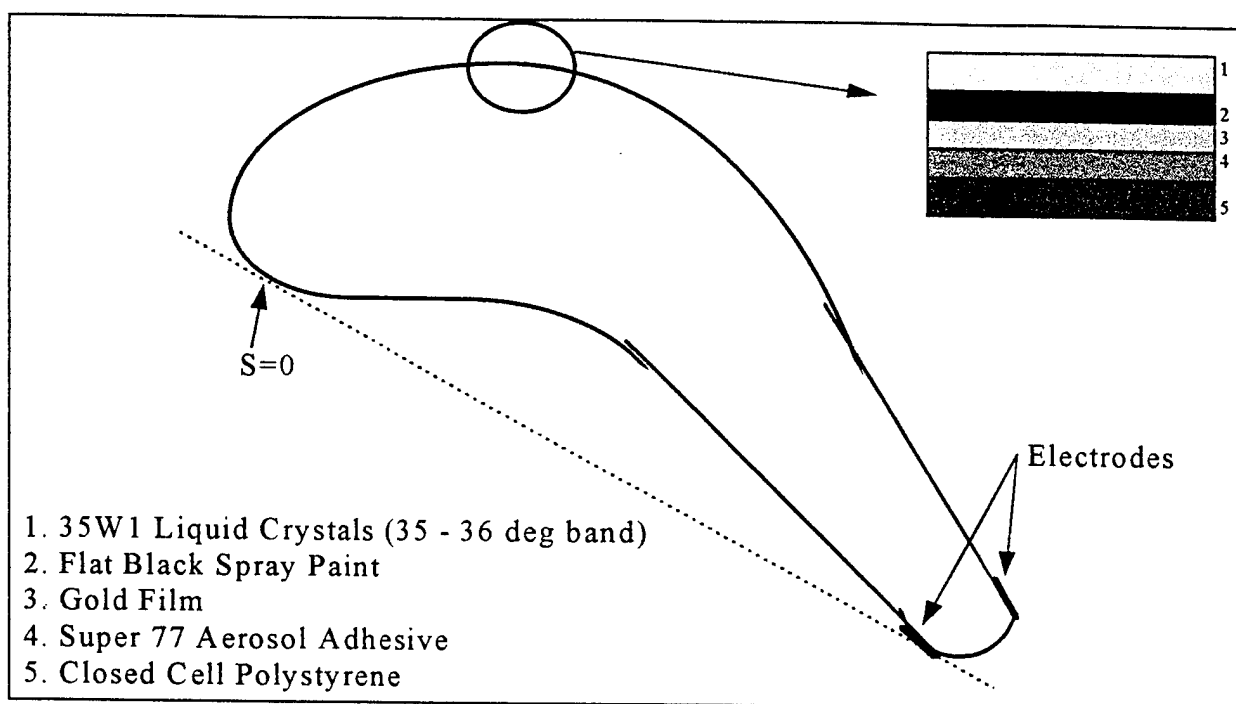


Figure 3: Test Section Diagram



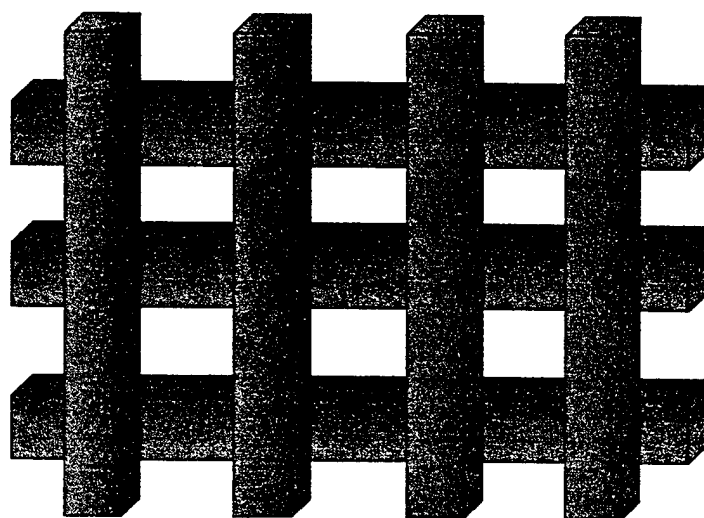
**Figure 4: Traversable Test Probe**

The setup for collecting heat transfer data centers on the test blade. The test blade is located in the center of the cascade. It is made of closed cell polystyrene, which is covered with Super 77 aerosol adhesive and a thin gold film with a resistance per square of 2.512 ohm/sq. This gold film is then covered with black paint and sprayed with 35W1 liquid crystals. The liquid crystals are active in the 35-36° Celsius range, with the yellow band indicating 35.7° Celsius. The gold acts as a conductor and provides resistance heating to the blade. Two electrodes at the trailing edge are connected to a DC power supply providing up to 5 amps. A multimeter is placed in series with the power supply and the blade to provide current readings. The entire test blade setup can be seen in Figure 4. This test blade allows for surface temperature and current readings to be taken which then allow heat transfer calculations to be performed.

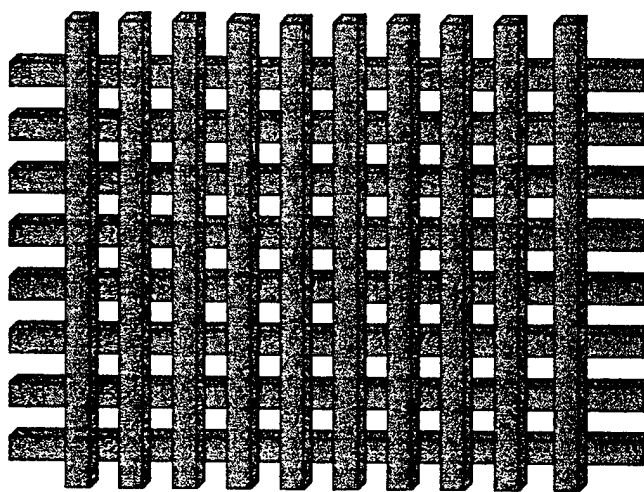


**Figure 5: Test Blade Setup**

The turbulence grids are constructed of square wood pieces which are nailed together in a square grid lattice. Two turbulence grids were constructed for this procedure, one grid of 1/2 in. diameter bars and one grid of 2 3/8 in. diameter bars.



**Figure 6: Grid of 2 3/8 in Diameter Bars**



**Figure 7: Grid of 1/2 in Diameter Bars**

The full list of equipment used in this investigation is as follows:

---

**Table of Equipment**

---

Cascade Wind Tunnel, U.S. Air Force Academy Aeronautics Lab  
 1/2 in. and 2 in. square mesh of square bars turbulence generation grids  
 Pitot-static tube  
 Pressure transducer  
 Torr pressure gage, SN 54258-1  
 Hot film anemometer, TSI Model 1210-20, SN 925113  
 K type Thermocouples  
 IFA 100 Intelligent Flow Analyzer  
 HP 3852A data acquisition/control unit  
 IBM compatible Pentium 90 computer  
 TV3 Software  
 SPSS Statistical Software  
 Microsoft Excel 4.0 Software  
 Styrofoam turbine blade assembly (See Figure 4)  
 HP 6434B DC power supply  
 Fluke 27/FM Multimeter

---

**Table 1: List of Equipment**

The instrument calibration for this experiment was already performed by laboratory personnel annually. The hot wire anemometer calibration is a fourth order curve fit which had been previously determined. The thermocouples, pressure transducers, thermometers and

barometers were calibrated by USAFA PMEL. The liquid crystals on the blade were also calibrated previously.

### **Experimental Procedure**

To obtain turbulent heat transfer and flow data use the following procedure:

- a. Using a clean tunnel configuration place the hot wire portion of the test probe at the center line position in front of the test blade. Ensure that the hot wire is directly into the flow. Raise the hot wire to a vertical position in the center of the gold section, ( $z = 9$  in.). With the probe located in this position take zero velocity data for the hot wire, pitot-static probe and temperature. Note the atmospheric pressure.
- b. Turn on the air allowing the tunnel to spool up to steady state (approximately 9 m/s). Then setting the TV3 software to take continuous data for 2.5 seconds at 6000 Hz on the hot wire, take hot wire, pitot-static and temperature data. Ensure that the temperature remains close to the zero velocity data. This data will be used to determine the integral length scale and turbulence intensity. In the same position set the TV3 to take continuous data at 15000 Hz for 1 second on the hot wire and take the same types of data. This data will be used to analyze the micro length scales and turbulence intensity. Note the turbulence intensity should be the same.
- c. Using the cooling flow, allow the tunnel to reach a steady state temperature of 25 Celsius. adjust the cooling flow to ensure that this temperature is maintained.
- d. When the tunnel has reached steady state carefully apply current from the power source to the test blade until the liquid crystals become active. When the liquid crystals are active note the position of the yellow band on both the suction and pressure sides as well as the current being applied. By gently adjusting the current, the yellow band can be moved over the entire blade

- noting the position and current at each position on the blade. Note any indications of flow phenomenon such as transition and Taylor-Görtler vortices. Use care not to overload the blade as it could cause the foam core to melt and ruin the test blade.
- e. Place the 2 3/8 in grid in the wind tunnel at the previously calculated distance for 10% turbulence intensity (approximately 72 in.). This is as far back from the blade as the test section allows. Take zero velocity and turbulent flow data as described above. Using SPSS analyze the continuous data to determine the turbulence intensity.
  - f. Move the data probe out of the flow and adjust the position of the grid forward to account for the distance between the probe and the turbine blade so that the blade itself is now seeing 10% turbulence intensity.
  - g. Run the tunnel up to steady state as describe for the clean tunnel case and take heat transfer data using the same procedure described in the clean tunnel case.
  - h. Replace the 2 3/8 in. turbulence generation grid with the 1/2 in. turbulence generation grid and repeat the same procedure used for the 2 3/8 in. grid. Take turbulence data and move the grid as necessary to match the large grid turbulence intensity.
  - i. Reduce all data for all flows and heat transfer to determine any possible relationship between length scales and heat transfer.

### Uncertainty Analysis

The uncertainty analysis of the heat transfer data was performed using the Kline-McClintock method. The equations of interest here are as follows:

$$q'' = \frac{I^2 R_{35.7}''}{w^2} \quad [12]$$

$$q_c'' = q'' - \varepsilon \sigma (T_{LC}^4 - T_\infty^4) - q_L'' \quad [13]$$

$$h = \frac{q_c''}{(T_{LC} - T_\infty)} \quad [14]$$

The equations were then placed in an Excel 4.0 spreadsheet along with the uncertainty equations in order to determine the expected uncertainty. Since our current ranges from 2.0 amps to 5.0 amps, the calculated uncertainty as per the spreadsheet in h ranges from 9.01% at 2.0 amps to 5.64% at 5.0 amps. This is well within acceptable parameters for this type of experiment. This spreadsheet is shown below in Figure 5.

				%Uncertainty	q'' Uncertainty	%q'' Uncertainty	qc'' Uncertainty	%qc'' Uncertainty	h Uncertainty	%h Uncertainty
Current	5.00 +/-	0.0050	Amps	0.10	3.01	0.20	3.01	0.21	0.28	0.21
Resistance	2.51 +/-	0.1256	Ohms/sq	5.00	75.31	5.00	75.31	5.20	7.04	5.20
FilmWidth	0.20 +/-	0.0002	m	0.10	-2.93	-0.19	-2.93	-0.20	-0.27	-0.20
T inf	25.00 +/-	0.1500	deg C	0.60	Not Used	Not Used	0.77	0.05	1.97	1.45
T LC	35.70 +/-	0.1500	deg C	0.42	Not Used	Not Used	-0.85	-0.06	-1.98	-1.46
Emmisivity	0.85 +/-	0.1500		17.65	Not Used	Not Used	-10.16	-0.70	-0.95	-0.70
Conduction	0.00 +/-	0.0000	W/m^2	0.00	Not Used	Not Used	0.00	0.00	0.00	0.00
S-B Const	5.67E-08	W/(m^2K^4)								
q'' =	1506.219 +/-	75.428	W/m^2	5.01	%Uncertainty					
qc'' =	1448.624 +/-	76.118	W/m^2	5.25	%Uncertainty					
h =	135.385 +/-	7.641	W/(m^2K)	5.64	%Uncertainty					

Figure 8: Uncertainty Analysis

## Results and Discussion

The results and discussion will be presented in three separate sections for each of the cascade tunnel configurations (clean, 1/2 in. grid, 2 3/8 in grid). After each configuration is presented and discussed and overall evaluation and discussion of the experiment will be presented.

### “Clean” Tunnel Configuration (No Turbulence Grid)

The turbulence data for all runs was taken at the center of the tunnel with the hot film anemometer aligned with the center of the test blade. All data is taken at this point over time.

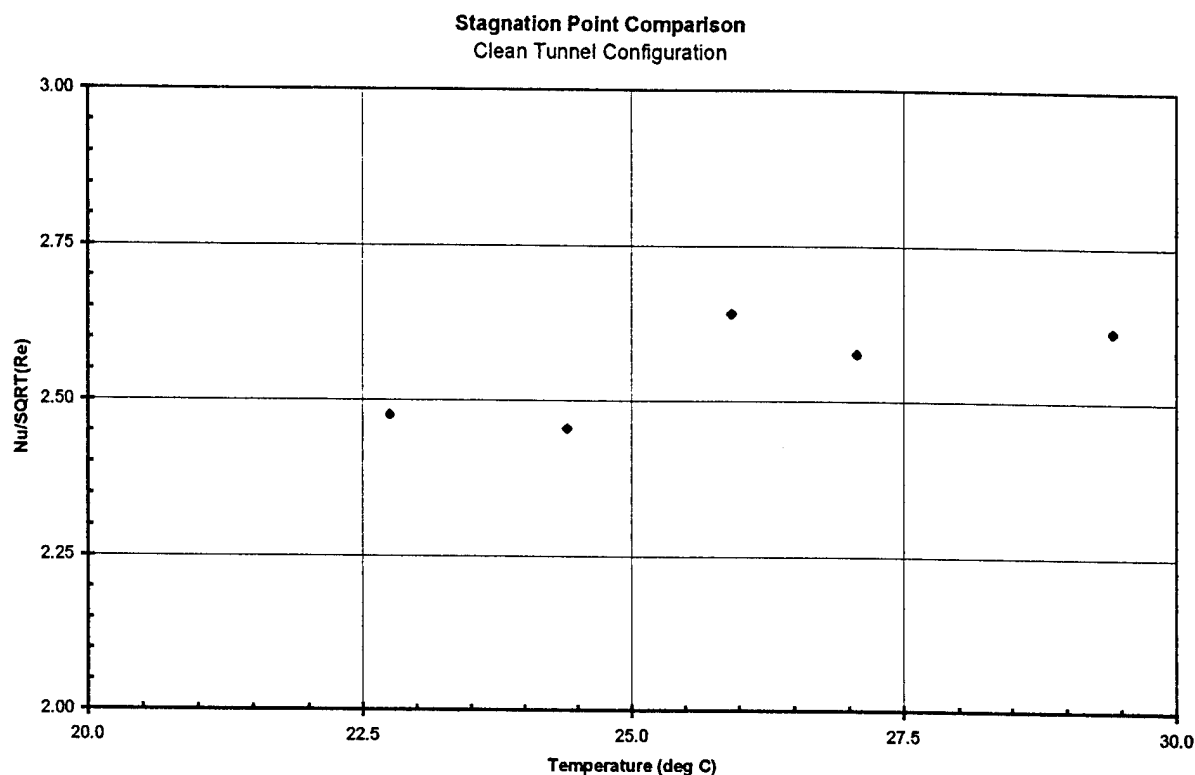
The key flow information for the clean tunnel run is tabulated below:

Flow Information	
Atmospheric Pressure	11.183 psia
Hot Film Zero Voltage	-5.351 V
Torr Meter Delta P	0.280 Torr
Mean Velocity	8.807 m/s @ 6000 Hz 8.799 m/s @ 15000 Hz
Standard Deviation	0.044 m/s @ 6000 Hz 0.040 m/s @ 15000 Hz
Turbulence Intensity	0.50% @ 6000 Hz
Micro-Length Scale	Infinite
Integral Length Scale	0.00543 m @ 15000 Hz 0.214 in @ 15000 Hz

**Table 2: Clean Tunnel Flow Information**

With this turbulence data taken, the heat transfer data was then taken and reduced. This data provided a baseline from which the effects of the turbulence could later be determined. This data was plotted against data provided by Capt Butler which was taken last semester. The data agreed nicely with last semester's data in all points but the stagnation point, which appeared to high on our run. Since this is an important point and there was significant fluctuation in temperature during the test run, it was decided to retest this point at several temperatures. This would determine whether there was a temperature dependency that was not removed by the data reduction or whether this was just an errant point. The results of the stagnation collection are shown below. The stagnation data points were relatively flat when retaken vs. temperature and all variation was within our experimental error. This supports the previous expectations. The average of these points was then entered as the stagnation heat transfer.

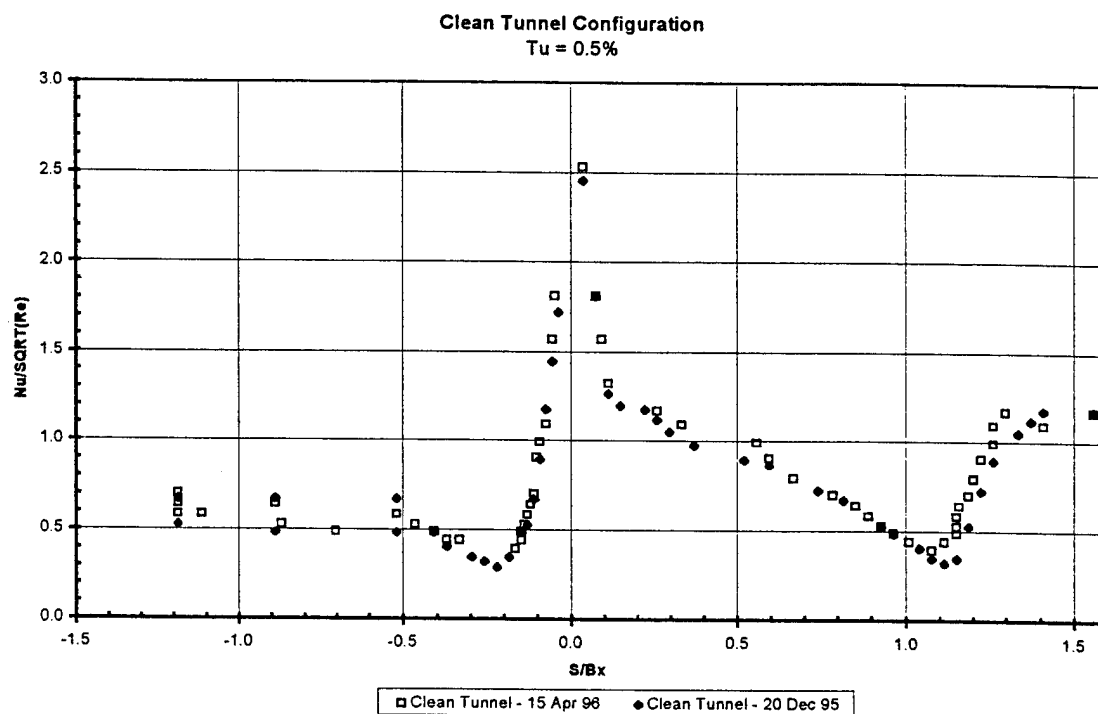




**Figure 9: Stagnation Point Comparison**

With the new stagnation point all the data for the clean tunnel lined up within the expected error and provided confidence in the data gathering technique. Some significant observations included an area on both the pressure side and the suction side where the foil had bubbled at the midspan of the blade. This bubbling caused flow irregularities such as separation and premature transition of the boundary layer. To account for this the data was taken from the top portion of the blade which was unaffected by these irregularities. While this does not necessarily invalidate the data it could be a source of error that later studies must consider.

Also of interest was the formation of spanwise variations on the pressure side of the blade that could represent Taylor-Görtler vortices. This is represented on the plot by the range of data points for a given Nusselt number.



**Figure 10: Clean Tunnel Comparison**

### 2 3/8 in Grid Configuration

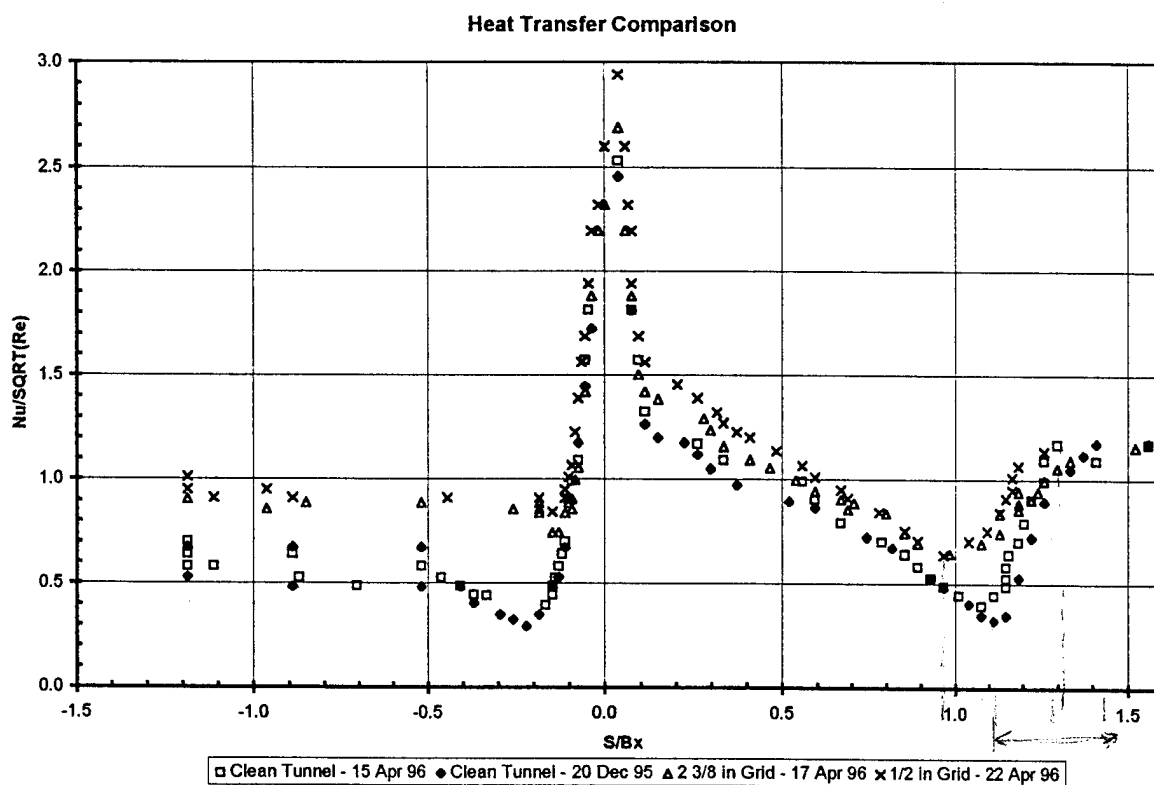
With the 2 3/8 in diameter bar turbulence grid in the test section, the turbulent flow data was reduced to give the following flow information.

#### Flow Information

Atmospheric Pressure	11.216 psia
Hot Film Zero Voltage	-5.36 V
Torr Meter Delta P	0.276 Torr
Mean Velocity	8.882 m/s @ 6000 Hz 8.658 m/s @ 15000 Hz
Standard Deviation	0.831 m/s @ 6000 Hz 0.881 m/s @ 15000 Hz
Turbulence Intensity	10.18% @ 6000 Hz
Micro-Length Scale	0.07053 m @ 6000 Hz 2.777 in @ 6000 Hz
Integral Length Scale	0.00837 m @ 15000 Hz 0.330 in @ 15000 Hz

**Table 3: 2 3/8 in Grid Flow Information**

This flow represents high turbulence intensity with large length scales and as expected affected the turbulence intensity by moving the transition point forward on the blade, and increasing heat transfer. The transition points moved forward 0.1875 in on the pressure side and 0.625 in on the suction side. At the stagnation point the heat transfer was increased by 6.25%. The spanwise distribution on the pressure side disappeared and post-transition heat transfer on the pressure side was dramatically increased by as much as 52 %. Elsewhere, increases in heat transfer were more moderate, on the order of the stagnation point increases. This distribution is shown in Figure 11.



**Figure 11: Heat Transfer Comparison**

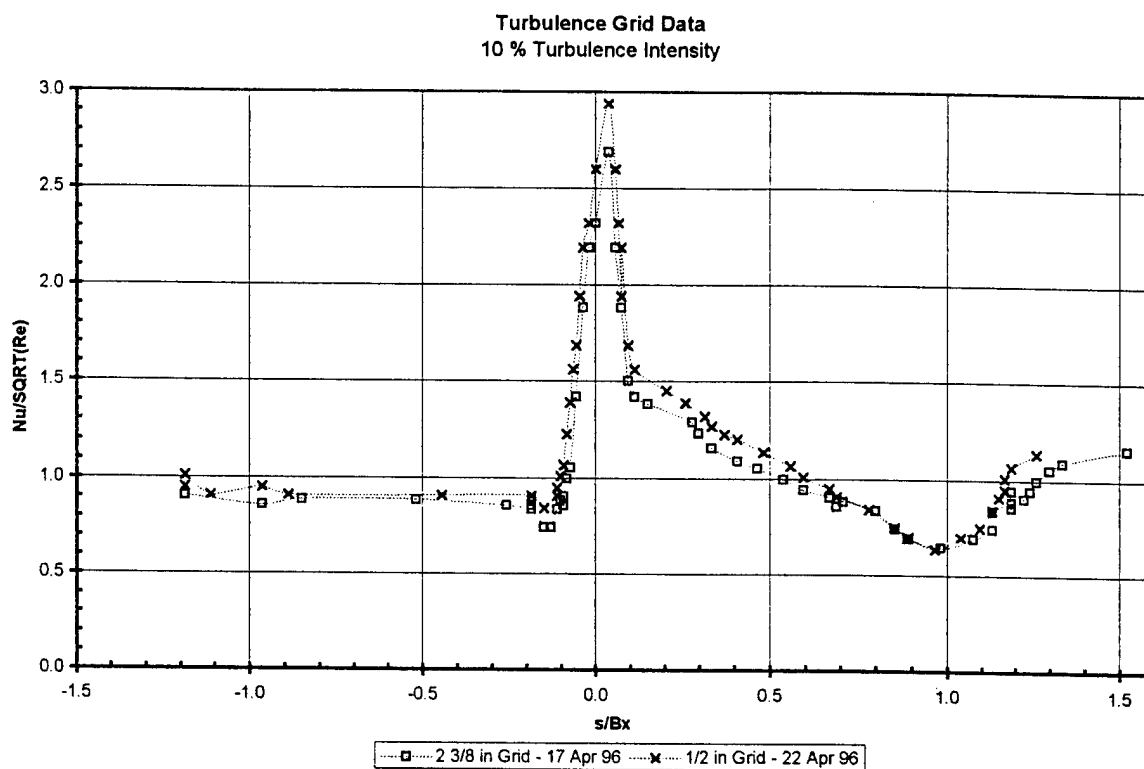
## 1/2 in Grid Configuration

With the 1/2 in turbulence grid in place the flow data was reduced to give the following flow information:

Flow Information	
Atmospheric Pressure	11.216 psia
Hot Film Zero Voltage	-5.34 V
Torr Meter Delta P	0.301 Torr
Mean Velocity	9.347 m/s @ 6000 Hz 8.998 m/s @ 15000 Hz
Standard Deviation	0.949 m/s @ 6000 Hz 0.894 m/s @ 15000 Hz
Turbulence Intensity	10.15% @ 6000 Hz
Micro-Length Scale	0.01320 m @ 6000 Hz 0.520 in @ 6000 Hz
Integral Length Scale	0.00490 m @ 15000 Hz 0.193 in @ 15000 Hz

**Table 4: 1/2 in Grid Flow Information**

The heat transfer data for this run, also plotted in Figure 11, shows the same trends as the 2 3/8 in grid. This is expected due to the nearly identical turbulence intensity. With this grid, however, the length scales are much smaller. The 1/2 in grid produced higher heat transfer rates than the 2 3/8 in grid until transition, which occurred at the same points as with the large grid. After transition the heat transfer characteristics were the same as the large grid characteristics. At stagnation the heat transfer was 16.2% higher than the clean tunnel and 9.4% higher than that produced by the large grid. Similarly the other data points before transition were higher than both the large grid and clean tunnel. Since this difference is greater than our uncertainty this represents a significant finding on the affect of length scales on heat transfer. The differences between the two grids are better highlighted in Figure 12 where just those two data sets are plotted. Additionally, lines are added to highlight the differences.



**Figure 12: Grid Comparison**

### Overall Discussion

The heat transfer characteristics of the turbine blade responded to turbulence intensity in the same manner as had already been shown by previous work such as Baughn et al. The effects of length scales appear to be primarily in the region of pre-transition heat transfer. The transition points are unaffected by the length scales, but a shorter length scale appears to cause a significant increase in heat transfer at the same turbulence intensity. This increase lasts until boundary layer transition where the free-stream turbulence becomes insignificant compared to the turbulent boundary layer.

## **Conclusions**

The effects of operating a turbine blade under high turbulence intensity, such as the 10.15% to 10.18% used in this investigation are an increase in heat transfer over the entire blade, the boundary layer transition points move forward on both blade surfaces, and the disappearance of spanwise heat transfer variations on the pressure side. In addition to these documented effects, it appears that smaller length scales at the same turbulence intensity produces higher heat transfer than that produced by longer length scales. In this test the stagnation temperature produced by the 1/2 in grid was 9% higher than that produced by the 2 3/8 in grid. The length scales appear to have no effect on transition location and the effects of differing length scales disappear after boundary layer transition. This is most likely due to the relative insignificance of the free-stream turbulence compared to the boundary layer turbulence. This investigation shows that length scales therefore have a significant impact on pre-transition heat transfer in turbine blades.

## **Recommendations**

The investigation of the effects of length scales on heat transfer should be continued. Tests should be conducted at different turbulence intensity levels and with more gradations of length scale in order to try and quantify the effect of length scales on the turbine heat transfer. Improvements on this experiment would be to include a better blade so that data can be taken over the entire blade. Also the people taking data could be more familiar with liquid crystals to allow for better readings of the crystals. Where possible have the same points measured by the same person in order to eliminate error introduced by having different people view the crystals. A greater understanding of length scales is essential to understanding turbulent heat transfer, especially since this investigation has shown that they have a significant impact on heat transfer.

**Acknowledgments**

We would like to acknowledge our sponsors, LtCol Barlow, LtCol Van Treuren, and Capt Butler, for their patient instruction and support for this project. Also we give thanks to SSgt Evans for providing facility support.

## References

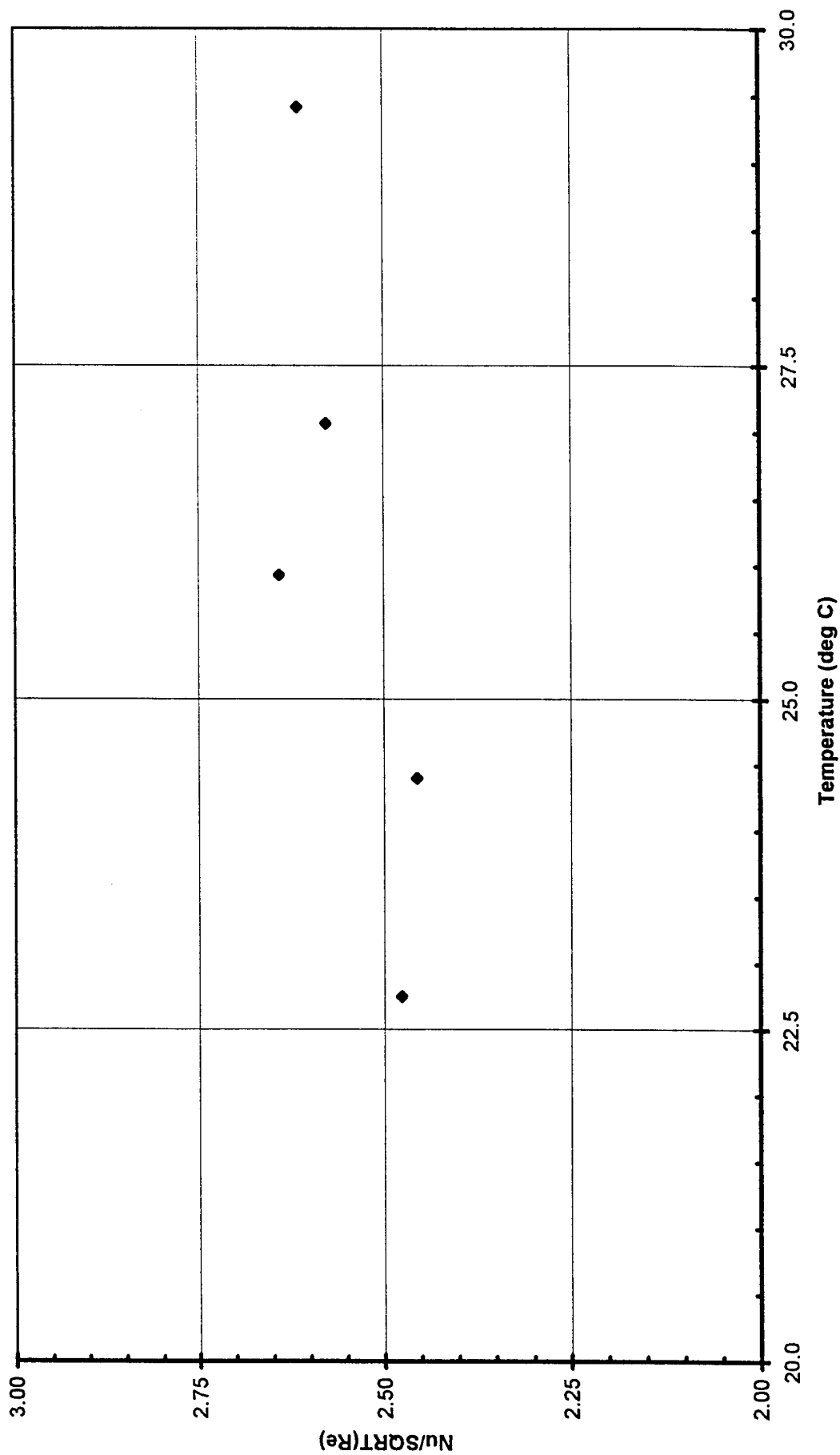
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**Appendix A:**  
**Heat Transfer Graphs**

Al

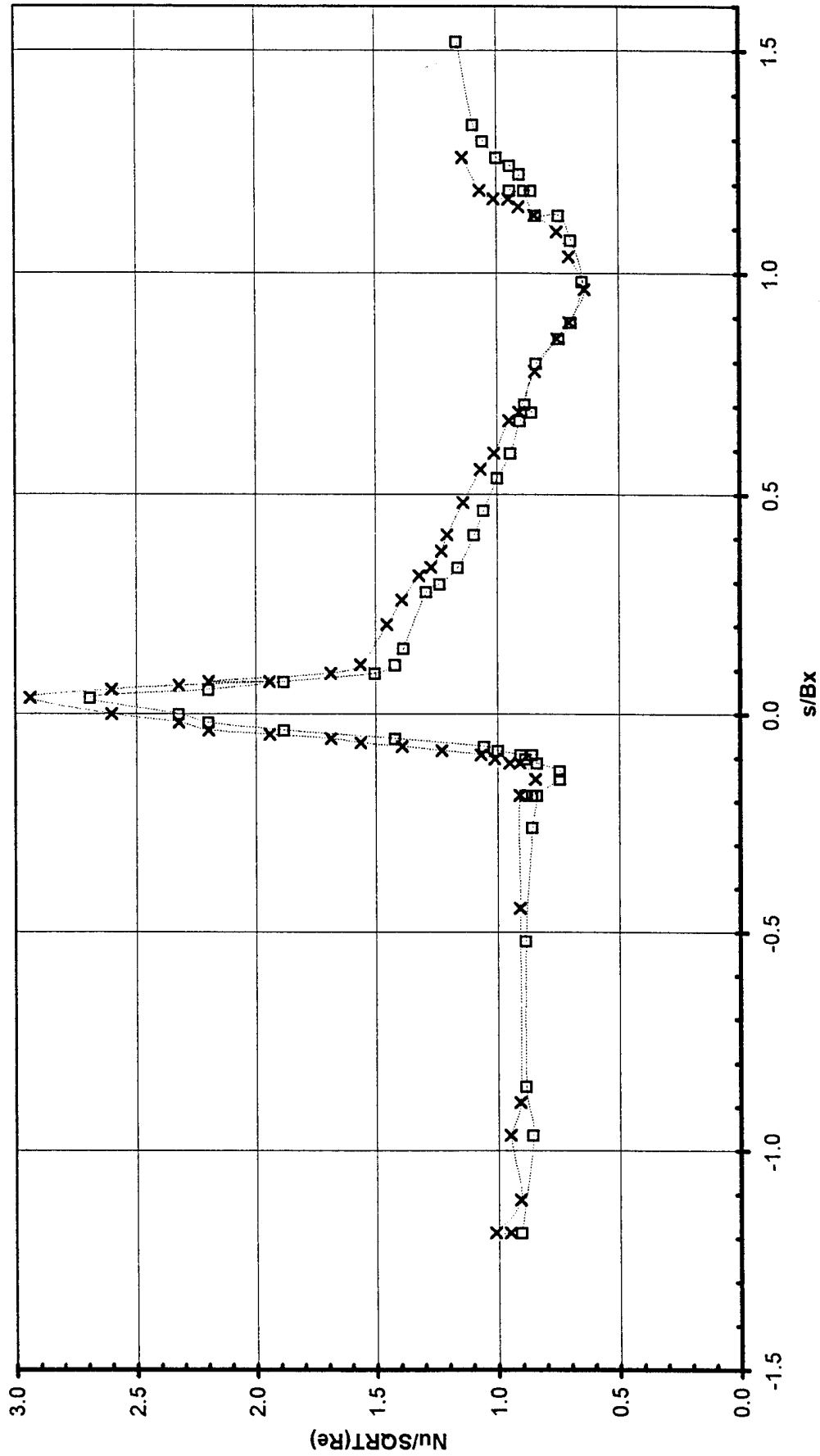
Stagnation Point Comparison  
Clean Tunnel Configuration



P inf =	11.311	psi		Rho =	0.9137	kg/m^3				
T inf =	24.400	C		Mu =	1.8337E-05	N s/m^2				
T lc =	35.700	C		k air =	0.0261	W/mK				
Delta P =	0.291	torr		V inf =	9.215	m/s				
L =	18.531	in		Bx =	6.740	in				
W =	8.039	in		Re =	78610.3					
R" =	2.512	Ohms/SQ		Cond. =	0	W/m^2				
Emmis. =	0.850			S-B Con. =	5.670E-08	W/m^2K^4				
Clean Tunnel Configuration -			Clean Tunnel - 20 Dec 95							
s (in)	s/Bx	Current (Amps)	T inf (C)	q" (W/m^2)	qc" (W/m^2)	h (W/m^2K)	St	Nu	Nu/SQRT(Re)	
-8.000	-1.1869	2.29	24.4	315.951	255.304	22.593	0.002665	148.152	0.5284	
-8.000	-1.1869	2.53	24.4	385.646	325.000	28.761	0.003392	188.596	0.6727	
-6.000	-0.8902	2.21	24.4	294.261	233.615	20.674	0.002438	135.565	0.4835	
-6.000	-0.8902	2.53	24.4	385.646	325.000	28.761	0.003392	188.596	0.6727	
-3.500	-0.5193	2.21	24.4	294.261	233.615	20.674	0.002438	135.565	0.4835	
-3.500	-0.5193	2.53	24.4	385.646	325.000	28.761	0.003392	188.596	0.6727	
-2.750	-0.4080	2.21	24.4	294.261	233.615	20.674	0.002438	135.565	0.4835	
-2.500	-0.3709	2.06	24.4	255.672	195.025	17.259	0.002036	113.172	0.4036	
-2.000	-0.2967	1.95	24.4	229.096	168.450	14.907	0.001758	97.750	0.3486	
-1.750	-0.2596	1.90	24.4	217.498	156.852	13.881	0.001637	91.020	0.3246	
-1.500	-0.2226	1.83	24.4	201.767	141.121	12.489	0.001473	81.892	0.2921	
-1.250	-0.1855	1.95	24.4	229.096	168.450	14.907	0.001758	97.750	0.3486	
-1.000	-0.1484	2.21	24.4	294.261	233.615	20.674	0.002438	135.565	0.4835	
-0.875	-0.1298	2.29	24.4	315.951	255.304	22.593	0.002665	148.152	0.5284	
-0.750	-0.1113	2.53	24.4	385.646	325.000	28.761	0.003392	188.596	0.6727	
-0.625	-0.0927	2.86	24.4	492.811	432.164	38.245	0.004511	250.783	0.8945	
-0.500	-0.0742	3.23	24.4	628.569	567.923	50.259	0.005928	329.562	1.1754	
-0.375	-0.0556	3.55	24.4	759.285	698.639	61.826	0.007292	405.416	1.4460	
-0.250	-0.0371	3.85	24.4	893.037	832.391	73.663	0.008688	483.032	1.7228	
0.250	0.0371	4.55	24.4	1247.300	1186.654	105.014	0.012385	688.608	2.4560	
0.500	0.0742	3.94	24.4	935.278	874.631	77.401	0.009129	507.544	1.8102	
0.750	0.1113	3.34	24.4	672.111	611.465	54.112	0.006382	354.829	1.2656	
1.000	0.1484	3.26	24.4	640.300	579.653	51.297	0.006050	336.370	1.1997	
1.500	0.2226	3.23	24.4	628.569	567.923	50.259	0.005928	329.562	1.1754	
1.750	0.2596	3.16	24.4	601.620	540.974	47.874	0.005646	313.924	1.1197	
2.000	0.2967	3.07	24.4	567.839	507.192	44.884	0.005294	294.321	1.0497	
2.500	0.3709	2.97	24.4	531.448	470.802	41.664	0.004914	273.204	0.9744	
3.500	0.5193	2.86	24.4	492.811	432.164	38.245	0.004511	250.783	0.8945	
4.000	0.5935	2.82	24.4	479.122	418.476	37.033	0.004368	242.839	0.8661	
5.000	0.7418	2.61	24.4	410.421	349.774	30.953	0.003651	202.972	0.7239	
5.500	0.8160	2.53	24.4	385.646	325.000	28.761	0.003392	188.596	0.6727	
6.250	0.9273	2.29	24.4	315.951	255.304	22.593	0.002665	148.152	0.5284	
6.500	0.9644	2.21	24.4	294.261	233.615	20.674	0.002438	135.565	0.4835	
7.000	1.0386	2.06	24.4	255.672	195.025	17.259	0.002036	113.172	0.4036	
7.250	1.0757	1.95	24.4	229.096	168.450	14.907	0.001758	97.750	0.3486	
7.500	1.1128	1.90	24.4	217.498	156.852	13.881	0.001637	91.020	0.3246	
7.750	1.1499	1.95	24.4	229.096	168.450	14.907	0.001758	97.750	0.3486	
8.000	1.1869	2.29	24.4	315.951	255.304	22.593	0.002665	148.152	0.5284	
8.250	1.2240	2.61	24.4	410.421	349.774	30.953	0.003651	202.972	0.7239	
8.500	1.2611	2.86	24.4	492.811	432.164	38.245	0.004511	250.783	0.8945	
9.000	1.3353	3.07	24.4	567.839	507.192	44.884	0.005294	294.321	1.0497	
9.250	1.3724	3.16	24.4	601.620	540.974	47.874	0.005646	313.924	1.1197	
9.500	1.4095	3.23	24.4	628.569	567.923	50.259	0.005928	329.562	1.1754	
10.500	1.5579	3.23	24.4	628.569	567.923	50.259	0.005928	329.562	1.1754	

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# Turbulence Grid Data 10 % Turbulence Intensity

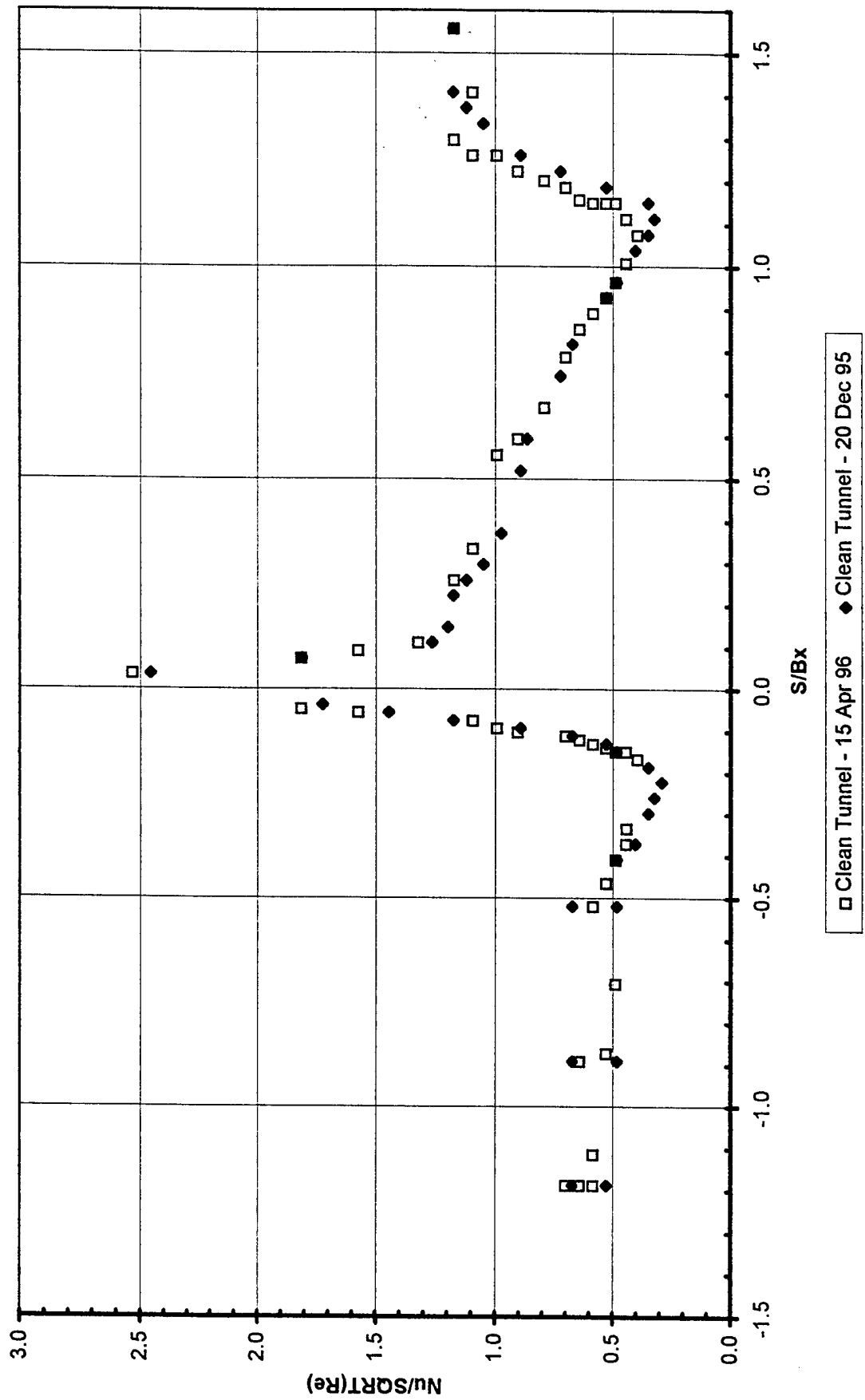


□ 2 3/8 in Grid - 17 Apr 96    x 1/2 in Grid - 22 Apr 96

P inf =	11.216 psi	Rho =	0.9039 kg/m <sup>3</sup>							
T inf =	25.100 C	Mu =	1.837E-05 N s/m <sup>2</sup>							
T ic =	35.700 C	k air =	0.0262 W/mK							
Delta P =	0.276 torr	V inf =	9.023 m/s							
L =	18.531 in	Bx =	6.740 in							
W =	8.039 in	Re =	76007.9							
R" =	2.512 Ohms/SQ	Cond. =	0 W/m <sup>2</sup>							
Emmis. =	0.850	S-B Con. =	5.670E-08 W/m <sup>2</sup> K <sup>4</sup>							
2 3/8 in. Grid at 72 3/4 in. -				2 3/8 in Grid - 17 Apr 96						
s (in)	s/Bx	Current (Amps)	T inf (C)	q" (W/m <sup>2</sup> )	qc" (W/m <sup>2</sup> )	h (W/m <sup>2</sup> K)	St	Nu	Nu/SQRT(Re)	
-8.000	-1.1869	2.79	25.0	467.303	409.504	38.129	0.004642	249.528	0.9051	
-6.500	-0.9644	2.73	24.9	447.385	389.382	36.121	0.004398	236.387	0.8574	
-5.750	-0.8531	2.70	25.4	439.213	383.817	37.373	0.004550	244.579	0.8871	
-3.500	-0.5193	2.70	25.4	439.213	383.817	37.373	0.004550	244.579	0.8871	
-1.750	-0.2596	2.73	24.9	447.385	389.382	36.121	0.004398	236.387	0.8574	
-1.250	-0.1855	2.64	25.4	419.910	364.308	35.335	0.004302	231.247	0.8388	
-1.250	-0.1855	2.70	25.4	439.213	383.817	37.373	0.004550	244.579	0.8871	
-1.250	-0.1855	2.73	24.9	447.385	389.382	36.121	0.004398	236.387	0.8574	
-1.000	-0.1484	2.52	25.3	382.604	326.439	31.328	0.003814	205.022	0.7437	
-0.875	-0.1298	2.52	25.3	382.604	326.439	31.328	0.003814	205.022	0.7437	
-0.750	-0.1113	2.64	25.4	419.910	364.308	35.335	0.004302	231.247	0.8388	
-0.688	-0.1020	2.70	25.4	439.213	383.817	37.373	0.004550	244.579	0.8871	
-0.625	-0.0927	2.73	24.9	447.385	389.382	36.121	0.004398	236.387	0.8574	
-0.625	-0.0927	2.79	25.0	467.303	409.504	38.129	0.004642	249.528	0.9051	
-0.563	-0.0835	2.91	24.9	510.193	452.292	42.035	0.005118	275.088	0.9978	
-0.500	-0.0742	2.98	25.0	535.033	477.183	44.389	0.005405	290.498	1.0537	
-0.375	-0.0556	3.38	25.1	688.306	631.375	59.733	0.007273	390.911	1.4179	
-0.250	-0.0371	3.85	25.2	893.037	836.208	79.261	0.009651	518.714	1.8815	
-0.125	-0.0185	4.14	25.2	1032.640	975.811	92.494	0.011262	605.312	2.1956	
0.000	0.0000	4.25	25.2	1085.684	1029.009	97.815	0.011910	640.131	2.3219	
0.250	0.0371	4.64	24.8	1297.132	1238.365	113.300	0.013795	741.471	2.6895	
0.375	0.0556	4.14	25.2	1032.640	975.811	92.494	0.011262	605.312	2.1956	
0.500	0.0742	3.85	25.2	893.037	836.208	79.261	0.009651	518.714	1.8815	
0.625	0.0927	3.47	25.1	725.449	668.518	63.247	0.007701	413.908	1.5013	
0.750	0.1113	3.38	25.1	688.306	631.375	59.733	0.007273	390.911	1.4179	
1.000	0.1484	3.35	25.1	674.125	617.092	58.271	0.007095	381.346	1.3832	
1.875	0.2782	3.25	25.1	636.378	579.038	54.370	0.006620	355.814	1.2906	
2.000	0.2967	3.18	25.1	609.260	552.073	51.984	0.006329	340.203	1.2340	
2.250	0.3338	3.11	24.9	582.732	524.831	48.776	0.005939	319.208	1.1578	
2.750	0.4080	3.04	24.9	554.965	496.911	46.053	0.005607	301.386	1.0932	
3.125	0.4636	2.98	25.0	535.033	477.183	44.389	0.005405	290.498	1.0537	
3.625	0.5378	2.91	24.9	510.193	452.292	42.035	0.005118	275.088	0.9978	
4.000	0.5935	2.85	24.9	487.655	429.550	39.773	0.004843	260.289	0.9441	
4.500	0.6677	2.79	25.0	467.303	409.504	38.129	0.004642	249.528	0.9051	
4.625	0.6862	2.73	24.9	447.385	389.382	36.121	0.004398	236.387	0.8574	
4.750	0.7047	2.70	25.4	439.213	383.817	37.373	0.004550	244.579	0.8871	
5.375	0.7975	2.64	25.4	419.910	364.308	35.335	0.004302	231.247	0.8388	
5.750	0.8531	2.52	25.3	382.604	326.439	31.328	0.003814	205.022	0.7437	
6.000	0.8902	2.45	25.3	361.643	305.428	29.284	0.003566	191.642	0.6951	
6.625	0.9829	2.37	25.3	338.411	282.554	27.274	0.003321	178.487	0.6474	
7.250	1.0757	2.45	25.3	361.643	305.428	29.284	0.003566	191.642	0.6951	
7.625	1.1313	2.52	25.3	382.604	326.439	31.328	0.003814	205.022	0.7437	
7.625	1.1313	2.64	25.4	419.910	364.308	35.335	0.004302	231.247	0.8388	
8.000	1.1869	2.70	25.4	439.213	383.817	37.373	0.004550	244.579	0.8871	
8.000	1.1869	2.73	24.9	447.385	389.382	36.121	0.004398	236.387	0.8574	
8.000	1.1869	2.85	24.9	487.655	429.550	39.773	0.004843	260.289	0.9441	
8.250	1.2240	2.79	25.0	467.303	409.504	38.129	0.004642	249.528	0.9051	
8.375	1.2426	2.85	24.9	487.655	429.550	39.773	0.004843	260.289	0.9441	
8.500	1.2611	2.91	24.9	510.193	452.292	42.035	0.005118	275.088	0.9978	
8.750	1.2982	2.98	25.0	535.033	477.183	44.389	0.005405	290.498	1.0537	
9.000	1.3353	3.04	24.9	554.965	496.911	46.053	0.005607	301.386	1.0932	
10.250	1.5208	3.11	24.9	582.732	524.831	48.776	0.005939	319.208	1.1578	

P inf =	11.396	psi	Rho =	0.9179	kg/m <sup>3</sup>				
T inf =	25.250	C	Mu =	1.8377E-05	N s/m <sup>2</sup>				
T lc =	35.700	C	k air =	0.0262	W/mK				
Delta P =	0.277	torr	V inf =	8.970	m/s				
L =	18.531	in	Bx =	6.740	in				
W =	8.039	in	Re =	76705.1					
R" =	2.512	Ohms/SQ	Cond. =	0	W/m <sup>2</sup>				
Emmis. =	0.850		S-B Con. =	5.670E-08	W/m <sup>2</sup> K <sup>4</sup>				
Clean Tunnel Configuration - Clean Tunnel - 15 Apr 96									
s (in)	s/Bx	Current (Amps)	T inf (C)	q" (W/m <sup>2</sup> )	qc" (W/m <sup>2</sup> )	h (W/m <sup>2</sup> K)	St	Nu	Nu/SQRT(Re)
-8.000	-1.1869	2.36	24.5	335.562	275.575	24.671	0.002975	161.387	0.5827
-8.000	-1.1869	2.45	24.6	361.643	301.809	27.092	0.003267	177.226	0.6399
-8.000	-1.1869	2.53	24.7	385.646	326.523	29.684	0.003580	194.179	0.7011
-7.500	-1.1128	2.36	24.5	335.562	275.575	24.671	0.002975	161.387	0.5827
-6.000	-0.8902	2.45	24.6	361.643	301.809	27.092	0.003267	177.226	0.6399
-5.875	-0.8717	2.27	24.5	310.456	250.317	22.350	0.002695	146.202	0.5279
-4.750	-0.7047	2.20	24.5	291.604	231.414	20.644	0.002490	135.041	0.4876
-3.500	-0.5193	2.36	24.5	335.562	275.575	24.671	0.002975	161.387	0.5827
-3.125	-0.4636	2.27	24.5	310.456	250.317	22.350	0.002695	146.202	0.5279
-2.750	-0.4080	2.20	24.5	291.604	231.414	20.644	0.002490	135.041	0.4876
-2.500	-0.3709	2.12	24.5	270.782	210.542	18.765	0.002263	122.751	0.4432
-2.250	-0.3338	2.02	25.5	245.839	190.648	16.636	0.002248	121.909	0.4402
-1.125	-0.1669	2.02	24.6	245.839	186.055	16.717	0.002016	109.353	0.3948
-1.000	-0.1484	2.12	24.5	270.782	210.542	18.765	0.002263	122.751	0.4432
-1.000	-0.1484	2.20	24.5	291.604	231.414	20.644	0.002490	135.041	0.4876
-0.938	-0.1391	2.27	24.5	310.456	250.317	22.350	0.002695	146.202	0.5279
-0.875	-0.1298	2.36	24.5	335.562	275.575	24.671	0.002975	161.387	0.5827
-0.813	-0.1205	2.45	24.6	361.643	301.809	27.092	0.003267	177.226	0.6399
-0.750	-0.1113	2.53	24.7	385.646	326.523	29.684	0.003580	194.179	0.7011
-0.688	-0.1020	2.76	25.2	458.951	402.378	38.322	0.004622	250.684	0.9051
-0.625	-0.0927	2.86	25.3	492.811	436.749	41.995	0.005065	274.713	0.9919
-0.500	-0.0742	2.97	25.4	531.448	475.898	46.204	0.005572	302.245	1.0913
-0.375	-0.0556	3.42	25.9	704.694	651.711	66.501	0.008020	435.021	1.5707
-0.313	-0.0464	3.64	26.0	798.272	745.701	76.718	0.009253	501.857	1.8120
0.250	0.0371	4.36	25.9	1145.305	1092.477	111.820	0.013486	731.474	2.5312
0.500	0.0742	3.64	26.0	798.272	745.701	76.718	0.009253	501.857	1.8120
0.625	0.0927	3.42	25.9	704.694	651.711	66.501	0.008020	435.021	1.5707
0.750	0.1113	3.17	25.8	605.434	552.142	55.998	0.006754	366.316	1.3226
1.750	0.2596	3.05	25.5	560.464	505.426	49.552	0.005976	324.145	1.1704
2.250	0.3338	2.97	25.4	531.448	475.898	46.204	0.005572	302.245	1.0913
3.750	0.5564	2.86	25.3	492.811	436.749	41.995	0.005065	274.713	0.9919
4.000	0.5935	2.76	25.2	458.951	402.378	38.322	0.004622	250.684	0.9051
4.500	0.6677	2.63	25.0	416.735	359.140	33.564	0.004048	219.564	0.7928
5.300	0.7864	2.53	24.7	385.646	326.523	29.684	0.003580	194.179	0.7011
5.750	0.8531	2.45	24.6	361.643	301.809	27.092	0.003267	177.226	0.6399
6.000	0.8902	2.36	24.5	335.562	275.575	24.671	0.002975	161.387	0.5827
6.250	0.9273	2.27	24.5	310.456	250.317	22.350	0.002695	146.202	0.5279
6.500	0.9644	2.20	24.5	291.604	231.414	20.644	0.002490	135.041	0.4876
6.800	1.0089	2.12	24.5	270.782	210.542	18.765	0.002263	122.751	0.4432
7.250	1.0757	2.02	24.6	245.839	186.055	16.717	0.002016	109.353	0.3948
7.500	1.1128	2.12	24.5	270.782	210.542	18.765	0.002263	122.751	0.4432
7.750	1.1499	2.20	24.5	291.604	231.414	20.644	0.002490	135.041	0.4876
7.750	1.1499	2.27	24.5	310.456	250.317	22.350	0.002695	146.202	0.5279
7.750	1.1499	2.36	24.5	335.562	275.575	24.671	0.002975	161.387	0.5827
7.800	1.1573	2.45	24.6	361.643	301.809	27.092	0.003267	177.226	0.6399
8.000	1.1869	2.53	24.7	385.646	326.523	29.684	0.003580	194.179	0.7011
8.100	1.2018	2.63	25.0	416.735	359.140	33.564	0.004048	219.564	0.7928
8.250	1.2240	2.76	25.2	458.951	402.378	38.322	0.004622	250.684	0.9051
8.500	1.2611	2.86	25.3	492.811	436.749	41.995	0.005065	274.713	0.9919
8.500	1.2611	2.97	25.4	531.448	475.898	46.204	0.005572	302.245	1.0913
8.750	1.2982	3.05	25.5	560.464	505.426	49.552	0.005976	324.145	1.1704
9.500	1.4095	2.97	25.4	531.448	475.898	46.204	0.005572	302.245	1.0913
10.500	1.5579	3.05	25.5	560.464	505.426	49.552	0.005976	324.145	1.1704

Clean Tunnel Configuration  
 $T_u = 0.5\%$



P inf =	11.400	psi		Rho =	0.9178	kg/m^3			
T inf =	25.400	C		Mu =	1.8384E-05	N s/m^2			
T ic =	35.700	C		k air =	0.0262	W/mK			
Delta P =	0.301	torr		V inf =	9.344	m/s			
L =	18.531	in		Bx =	6.740	in			
W =	8.039	in		Re =	79855.6				
R" =	2.512	Ohms/SQ		Cond. =	0	W/m^2			
Emmis. =	0.850			S-B Con. =	5.670E-08	W/m^2K^4			
1/2 in Grid at 15 in -			1/2 in Grid - 22 Apr 96						
s (in)	s/Bx	Current (Amps)	T inf (C)	q" (W/m^2)	qc" (W/m^2)	h (W/m^2K)	St	Nu	Nu/SQRT(Re)
-8.000	-1.1869	2.81	25.5	475.730	420.539	41.108	0.004760	268.799	0.9512
-8.000	-1.1869	2.89	25.5	503.204	447.910	43.699	0.005060	285.735	1.0111
-7.500	-1.1128	2.76	25.4	458.951	403.606	39.338	0.004555	257.222	0.9102
-6.500	-0.9644	2.81	25.5	475.730	420.539	41.108	0.004760	268.799	0.9512
-6.000	-0.8902	2.76	25.4	458.951	403.606	39.338	0.004555	257.222	0.9102
-3.000	-0.4451	2.76	25.4	458.951	403.606	39.338	0.004555	257.222	0.9102
-1.250	-0.1855	2.76	25.4	458.951	403.606	39.338	0.004555	257.222	0.9102
-1.000	-0.1484	2.67	25.5	429.507	374.213	36.509	0.004228	238.722	0.8448
-0.750	-0.1113	2.76	25.4	458.951	403.606	39.338	0.004555	257.222	0.9102
-0.750	-0.1113	2.81	25.5	475.730	420.539	41.108	0.004760	268.799	0.9512
-0.688	-0.1020	2.89	25.5	503.204	447.910	43.699	0.005060	285.735	1.0111
-0.625	-0.0927	2.96	25.5	527.876	472.582	46.106	0.005339	301.474	1.0668
-0.563	-0.0835	3.16	25.4	601.620	546.070	53.016	0.006139	346.664	1.2267
-0.500	-0.0742	3.35	25.4	676.142	620.438	60.062	0.006955	392.731	1.3898
-0.438	-0.0649	3.52	25.5	746.506	691.264	67.506	0.007817	441.409	1.5620
-0.375	-0.0556	3.66	25.4	807.068	751.467	72.887	0.008440	476.594	1.6865
-0.313	-0.0464	3.94	25.2	935.278	878.858	83.941	0.009720	548.870	1.9423
-0.250	-0.0371	4.15	25.4	1037.634	981.828	94.863	0.010985	620.287	2.1950
-0.125	-0.0185	4.26	25.4	1093.370	1037.616	100.350	0.011621	656.165	2.3220
0.000	0.0000	4.50	25.3	1220.037	1164.180	112.373	0.013013	734.781	2.6002
0.250	0.0371	4.78	25.3	1376.588	1320.577	127.101	0.014718	831.085	2.9410
0.375	0.0556	4.50	25.3	1220.037	1164.180	112.373	0.013013	734.781	2.6002
0.438	0.0649	4.26	25.4	1093.370	1037.616	100.350	0.011621	656.165	2.3220
0.500	0.0742	3.94	25.2	935.278	878.858	83.941	0.009720	548.870	1.9423
0.500	0.0742	4.15	25.4	1037.634	981.828	94.863	0.010985	620.287	2.1950
0.625	0.0927	3.66	25.4	807.068	751.467	72.887	0.008440	476.594	1.6865
0.750	0.1113	3.52	25.5	746.506	691.264	67.506	0.007817	441.409	1.5620
1.375	0.2040	3.43	25.3	708.821	652.810	62.831	0.007276	410.836	1.4538
1.750	0.2596	3.35	25.4	676.142	620.438	60.062	0.006955	392.731	1.3898
2.125	0.3153	3.26	25.5	640.300	585.006	57.074	0.006609	373.193	1.3206
2.250	0.3338	3.21	25.4	618.877	563.532	54.925	0.006360	359.144	1.2709
2.500	0.3709	3.16	25.4	601.620	546.070	53.016	0.006139	346.664	1.2267
2.750	0.4080	3.12	25.5	586.486	531.345	51.991	0.006021	339.957	1.2030
3.250	0.4822	3.06	25.4	564.145	508.339	49.115	0.005688	321.152	1.1365
3.750	0.5564	2.96	25.5	527.876	472.582	46.106	0.005339	301.474	1.0668
4.000	0.5935	2.89	25.5	503.204	447.910	43.699	0.005060	285.735	1.0111
4.500	0.6677	2.81	25.5	475.730	420.539	41.108	0.004760	268.799	0.9512
4.625	0.6862	2.76	25.4	458.951	403.606	39.338	0.004555	257.222	0.9102
5.250	0.7789	2.67	25.5	429.507	374.213	36.509	0.004228	238.722	0.8448
5.750	0.8531	2.56	25.3	394.846	338.784	32.575	0.003772	213.004	0.7538
6.000	0.8902	2.47	25.4	367.572	312.226	30.431	0.003524	198.985	0.7042
6.500	0.9644	2.38	25.4	341.273	285.518	27.613	0.003198	180.555	0.6389
7.000	1.0386	2.47	25.4	367.572	312.226	30.431	0.003524	198.985	0.7042
7.375	1.0942	2.56	25.3	394.846	338.784	32.575	0.003772	213.004	0.7538
7.625	1.1313	2.67	25.5	429.507	374.213	36.509	0.004228	238.722	0.8448
7.750	1.1499	2.76	25.4	458.951	403.606	39.338	0.004555	257.222	0.9102
7.875	1.1684	2.81	25.5	475.730	420.539	41.108	0.004760	268.799	0.9512
7.875	1.1684	2.89	25.5	503.204	447.910	43.699	0.005060	285.735	1.0111
8.000	1.1869	2.96	25.5	527.876	472.582	46.106	0.005339	301.474	1.0668
8.500	1.2611	3.06	25.4	564.145	508.339	49.115	0.005688	321.152	1.1365

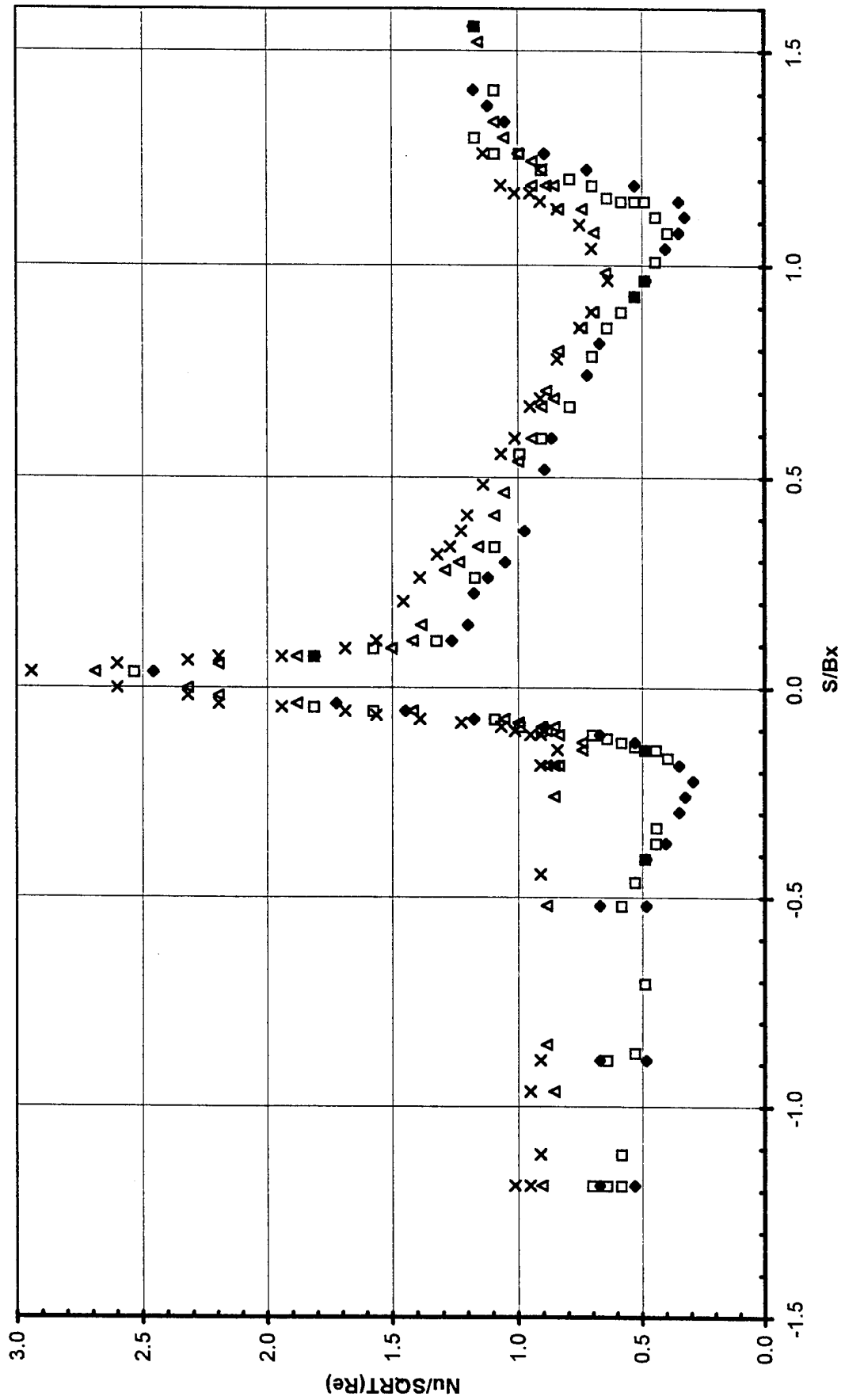


P inf =	11.280	psi			Rho =	0.9093	kg/m^3			
T inf =	25.000	C			Mu =	1.8365E-05	N s/m^2			
T lc =	35.700	C			k air =	0.0262	W/mK			
Delta P =	0.323	torr			V inf =	9.732	m/s			
L =	18.531	in			Bx =	6.740	in			
W =	8.039	in			Re =	82494.8				
R" =	2.512	Ohms/SQ			Cond. =	0	W/m^2			
Emmis. =	0.850				S-B Con. =	5.670E-08	W/m^2K^4			
Clean Tunnel Stagnation Points -			01 May 96, 15 Apr 96, & 20 Dec 96							
s (in)	s/Bx	Current (Amps)	T inf (C)	q" (W/m^2)	qc" (W/m^2)	h (W/m^2K)	St	Nu	Nu/SQRT(Re)	
0.250	0.0371	4.12	27.1	1022.687	975.762	113.066	0.012687	740.154	2.5770	
0.250	0.0371	3.54	29.4	755.013	720.473	114.725	0.012874	751.012	2.6148	
0.250	0.0371	4.95	22.8	1476.245	1407.302	108.672	0.012194	711.388	2.4768	
0.250	0.0371	4.36	25.9	1145.305	1092.477	111.820	0.013486	731.474	2.6411	
0.250	0.0371	4.55	24.4	1247.300	1186.654	105.014	0.012385	688.608	2.4560	

**Appendix B:**  
**Heat Transfer Data Sheets**

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# Heat Transfer Comparison

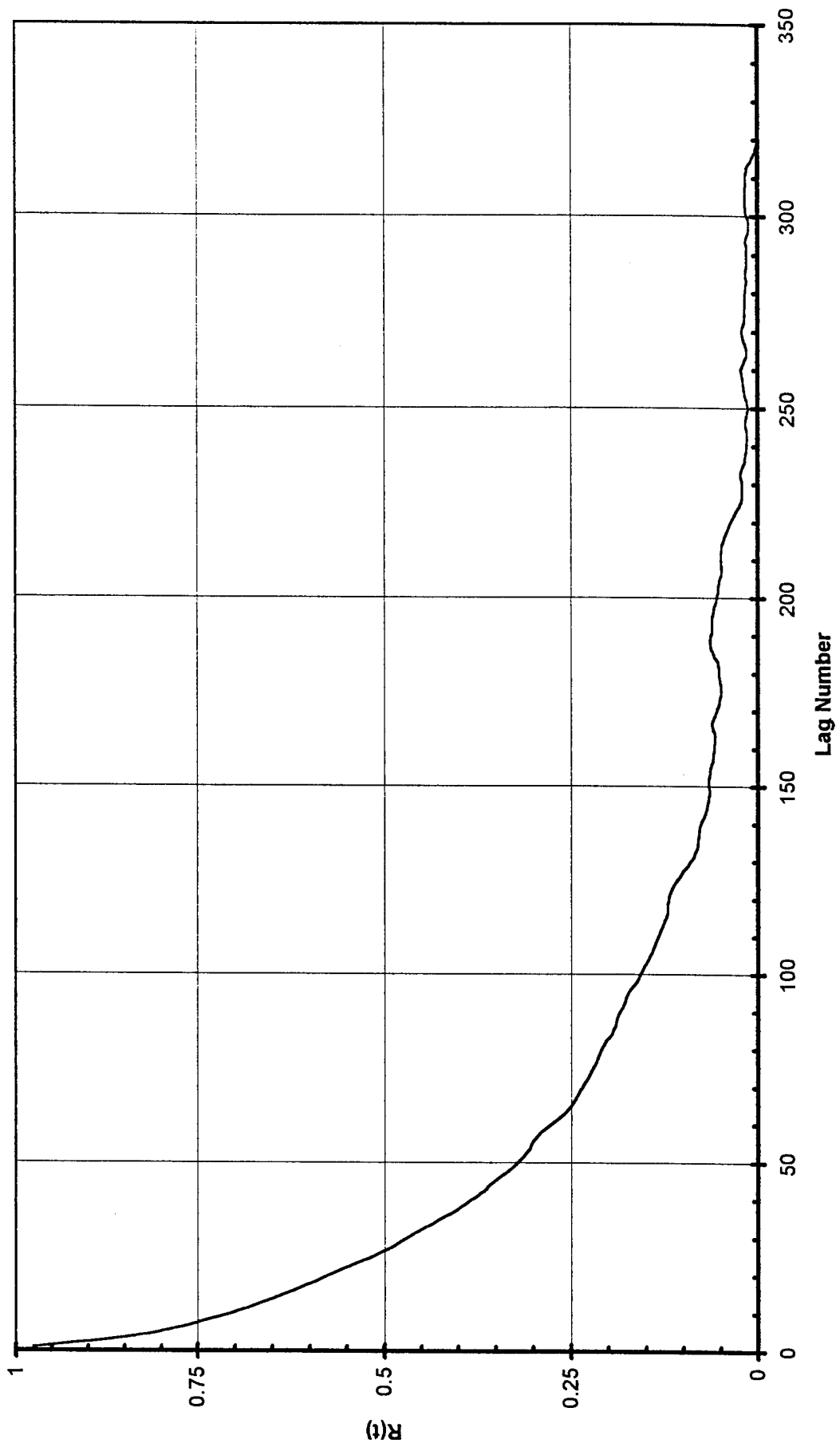


□ Clean Tunnel - 15 Apr 96 ♦ Clean Tunnel - 20 Dec 95 Δ 2 3/8 in Grid - 17 Apr 96 x 1/2 in Grid - 22 Apr 96

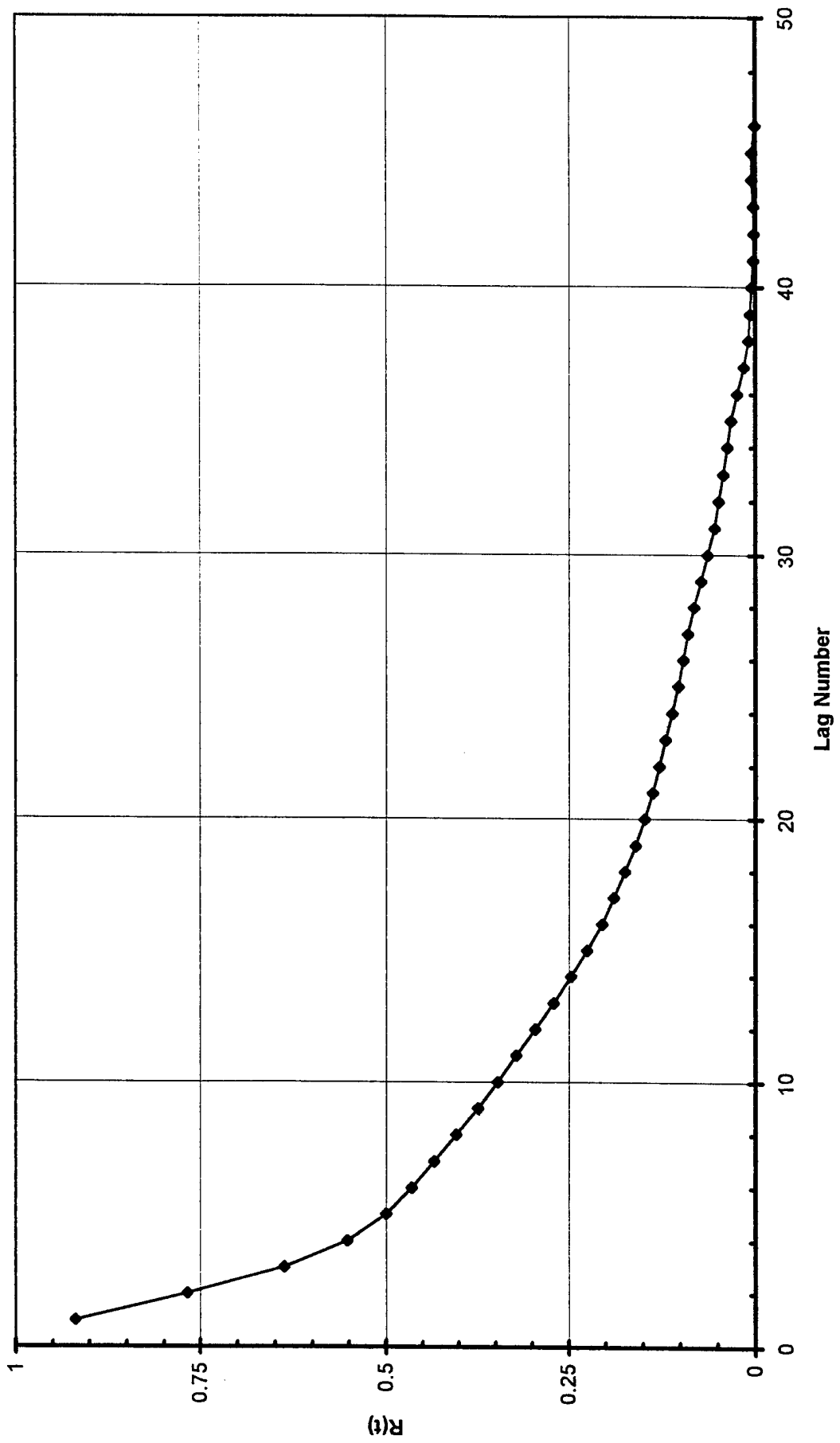
Handwritten notes: "Grid 2 3/8" and "17 Apr 96".

## **Appendix C: Length Scale Data Sheets**

**Autocorrelation Results**  
2 3/8 in Grid at 72 3/4 in



Autocorrelation Results  
1/2 in Grid at 15 in.



Integral Length Scale					
Lag	Corr.	Average	U =	8.658 m/s	
1	0.976	0.9505	Freq =	6000 Hz	
2	0.925	0.8995	Integral =	0.070532 m	
3	0.874	0.854		2.776866 in	
4	0.834	0.8195			
5	0.805	0.793			
6	0.781	0.7705	Micro-length Scale		
7	0.76	0.7505	Lag 1 =	0.995	
8	0.741	0.732	Freq =	15000 Hz	
9	0.723	0.7145	U =	8.882 m/s	
10	0.706	0.698	Micro =	0.008374 m	
11	0.69	0.683		0.329686 in	
12	0.676	0.669			
13	0.662	0.655			
14	0.648	0.6415			
15	0.635	0.6285			
16	0.622	0.616			
17	0.61	0.604			
18	0.598	0.5925			
19	0.587	0.5815			
20	0.576	0.5705			
21	0.565	0.559			
22	0.553	0.547			
23	0.541	0.5345			
24	0.528	0.522			
25	0.516	0.5105			
26	0.505	0.5			
27	0.495	0.4905			
28	0.486	0.482			
29	0.478	0.474			
30	0.47	0.4655			
31	0.461	0.4565			
32	0.452	0.447			
33	0.442	0.4375			
34	0.433	0.4285			
35	0.424	0.4195			
36	0.415	0.4105			
37	0.406	0.402			
38	0.398	0.3945			
39	0.391	0.3875			
40	0.384	0.38			
41	0.376	0.3725			
42	0.369	0.366			
43	0.363	0.3605			
44	0.358	0.355			
45	0.352	0.3485			
46	0.345	0.3415			
47	0.338	0.335			
48	0.332	0.329			
49	0.326	0.3235			
50	0.321	0.3185			
51	0.316	0.314			
52	0.312	0.31			
53	0.308	0.306			
54	0.304	0.303			
55	0.302	0.3005			
56	0.299	0.297			
57	0.295	0.2925			
58	0.29	0.287			
59	0.284	0.2805			
60	0.277	0.274			
61	0.271	0.2675			

62	0.264	0.2615				
63	0.259	0.2565				
64	0.254	0.252				
65	0.25	0.2485				
66	0.247	0.2455				
67	0.244	0.2425				
68	0.241	0.2395				
69	0.238	0.2365				
70	0.235	0.2335				
71	0.232	0.2305				
72	0.229	0.2275				
73	0.226	0.2245				
74	0.223	0.222				
75	0.221	0.2195				
76	0.218	0.217				
77	0.216	0.215				
78	0.214	0.213				
79	0.212	0.211				
80	0.21	0.2085				
81	0.207	0.2055				
82	0.204	0.202				
83	0.2	0.198				
84	0.196	0.195				
85	0.194	0.193				
86	0.192	0.191				
87	0.19	0.1895				
88	0.189	0.188				
89	0.187	0.186				
90	0.185	0.1835				
91	0.182	0.181				
92	0.18	0.179				
93	0.178	0.177				
94	0.176	0.175				
95	0.174	0.1725				
96	0.171	0.169				
97	0.167	0.165				
98	0.163	0.1615				
99	0.16	0.159				
100	0.158	0.1565				
101	0.155	0.154				
102	0.153	0.1515				
103	0.15	0.1485				
104	0.147	0.146				
105	0.145	0.1435				
106	0.142	0.141				
107	0.14	0.139				
108	0.138	0.137				
109	0.136	0.135				
110	0.134	0.133				
111	0.132	0.131				
112	0.13	0.129				
113	0.128	0.127				
114	0.126	0.125				
115	0.124	0.123				
116	0.122	0.1215				
117	0.121	0.121				
118	0.121	0.121				
119	0.121	0.1205				
120	0.12	0.1195				
121	0.119	0.118				
122	0.117	0.116				
123	0.115	0.1135				
124	0.112	0.1105				
125	0.109	0.107				
126	0.105	0.1035				



127	0.102	0.1				
128	0.098	0.096				
129	0.094	0.0925				
130	0.091	0.089				
131	0.087	0.086				
132	0.085	0.084				
133	0.083	0.082				
134	0.081	0.0805				
135	0.08	0.08				
136	0.08	0.0795				
137	0.079	0.079				
138	0.079	0.0785				
139	0.078	0.0775				
140	0.077	0.076				
141	0.075	0.0735				
142	0.072	0.071				
143	0.07	0.0695				
144	0.069	0.0685				
145	0.068	0.0675				
146	0.067	0.0665				
147	0.066	0.0655				
148	0.065	0.065				
149	0.065	0.0655				
150	0.066	0.066				
151	0.066	0.066				
152	0.066	0.0655				
153	0.065	0.0645				
154	0.064	0.0635				
155	0.063	0.0625				
156	0.062	0.061				
157	0.06	0.06				
158	0.06	0.0595				
159	0.059	0.0585				
160	0.058	0.058				
161	0.058	0.0575				
162	0.057	0.057				
163	0.057	0.0575				
164	0.058	0.059				
165	0.06	0.0605				
166	0.061	0.061				
167	0.061	0.06				
168	0.059	0.058				
169	0.057	0.056				
170	0.055	0.0545				
171	0.054	0.053				
172	0.052	0.0515				
173	0.051	0.0505				
174	0.05	0.0495				
175	0.049	0.049				
176	0.049	0.0495				
177	0.05	0.0505				
178	0.051	0.0515				
179	0.052	0.052				
180	0.052	0.052				
181	0.052	0.0525				
182	0.053	0.0535				
183	0.054	0.0555				
184	0.057	0.058				
185	0.059	0.06				
186	0.061	0.062				
187	0.063	0.0635				
188	0.064	0.064				
189	0.064	0.0635				
190	0.063	0.062				
191	0.061	0.061				

192	0.061	0.061				
193	0.061	0.061				
194	0.061	0.061				
195	0.061	0.0605				
196	0.06	0.0595				
197	0.059	0.0585				
198	0.058	0.057				
199	0.056	0.0555				
200	0.055	0.0545				
201	0.054	0.0535				
202	0.053	0.053				
203	0.053	0.0525				
204	0.052	0.0515				
205	0.051	0.05				
206	0.049	0.0485				
207	0.048	0.048				
208	0.048	0.0485				
209	0.049	0.049				
210	0.049	0.049				
211	0.049	0.049				
212	0.049	0.0485				
213	0.048	0.048				
214	0.048	0.047				
215	0.046	0.0455				
216	0.045	0.044				
217	0.043	0.042				
218	0.041	0.04				
219	0.039	0.038				
220	0.037	0.0355				
221	0.034	0.0325				
222	0.031	0.03				
223	0.029	0.0275				
224	0.026	0.025				
225	0.024	0.023				
226	0.022	0.0215				
227	0.021	0.021				
228	0.021	0.021				
229	0.021	0.021				
230	0.021	0.0215				
231	0.022	0.0225				
232	0.023	0.023				
233	0.023	0.0225				
234	0.022	0.021				
235	0.02	0.019				
236	0.018	0.0175				
237	0.017	0.0165				
238	0.016	0.0155				
239	0.015	0.015				
240	0.015	0.0145				
241	0.014	0.014				
242	0.014	0.014				
243	0.014	0.0145				
244	0.015	0.0155				
245	0.016	0.016				
246	0.016	0.016				
247	0.016	0.0155				
248	0.015	0.0145				
249	0.014	0.0135				
250	0.013	0.0135				
251	0.014	0.0145				
252	0.015	0.016				
253	0.017	0.0175				
254	0.018	0.0185				
255	0.019	0.0195				
256	0.02	0.02				

257	0.02	0.0205			
258	0.021	0.0215			
259	0.022	0.0225			
260	0.023	0.022			
261	0.021	0.02			
262	0.019	0.018			
263	0.017	0.016			
264	0.015	0.015			
265	0.015	0.0155			
266	0.016	0.017			
267	0.018	0.019			
268	0.02	0.0205			
269	0.021	0.0215			
270	0.022	0.0215			
271	0.021	0.02			
272	0.019	0.0185			
273	0.018	0.018			
274	0.018	0.018			
275	0.018	0.018			
276	0.018	0.0175			
277	0.017	0.017			
278	0.017	0.017			
279	0.017	0.017			
280	0.017	0.0165			
281	0.016	0.016			
282	0.016	0.0155			
283	0.015	0.0155			
284	0.016	0.016			
285	0.016	0.016			
286	0.016	0.0155			
287	0.015	0.015			
288	0.015	0.015			
289	0.015	0.015			
290	0.015	0.015			
291	0.015	0.015			
292	0.015	0.0155			
293	0.016	0.016			
294	0.016	0.0155			
295	0.015	0.014			
296	0.013	0.0125			
297	0.012	0.012			
298	0.012	0.0125			
299	0.013	0.014			
300	0.015	0.0155			
301	0.016	0.016			
302	0.016	0.0165			
303	0.017	0.017			
304	0.017	0.017			
305	0.017	0.017			
306	0.017	0.017			
307	0.017	0.0165			
308	0.016	0.016			
309	0.016	0.016			
310	0.016	0.016			
311	0.016	0.0155			
312	0.015	0.0145			
313	0.014	0.0125			
314	0.011	0.01			
315	0.009	0.0075			
316	0.006	0.005			
317	0.004	0.0035			
318	0.003	0.002			
319	0.001	0.0005			

Integral Length Scale						
Lag	Corr.	Average		U =	9.347 m/s	
1	0.919	0.8435		Freq =	6000 Hz	
2	0.768	0.703		Integral =	0.013199 m	
3	0.638	0.595			0.519636 in	
4	0.552	0.526				
5	0.5	0.4825				
6	0.465	0.4495		Micro-length Scale		
7	0.434	0.419		Lag 1 =	0.985	
8	0.404	0.389		Freq =	15000 Hz	
9	0.374	0.3605		U =	8.998 m/s	
10	0.347	0.3345		Micro =	0.004898 m	
11	0.322	0.309			0.19283 in	
12	0.296	0.2835				
13	0.271	0.259				
14	0.247	0.236				
15	0.225	0.215				
16	0.205	0.197				
17	0.189	0.1815				
18	0.174	0.167				
19	0.16	0.154				
20	0.148	0.1425				
21	0.137	0.1325				
22	0.128	0.124				
23	0.12	0.1155				
24	0.111	0.107				
25	0.103	0.0995				
26	0.096	0.093				
27	0.09	0.086				
28	0.082	0.077				
29	0.072	0.0675				
30	0.063	0.0585				
31	0.054	0.051				
32	0.048	0.045				
33	0.042	0.0395				
34	0.037	0.0345				
35	0.032	0.028				
36	0.024	0.0195				
37	0.015	0.012				
38	0.009	0.008				
39	0.007	0.006				
40	0.005	0.004				
41	0.003	0.0025				
42	0.002	0.0025				
43	0.003	0.004				
44	0.005	0.005				
45	0.005	0.003				
46	0.001	0.0005				

## **Appendix D: Uncertainty Analysis**

					% Uncertainty	q" Uncertainty	% q" Uncertainty	qc" Uncertainty	% qc" Uncertainty	h Uncertainty	% h Uncertainty
Current	5.00 +/-	0.0050	Amps		0.10	3.01	0.20	3.01	0.21	0.28	0.21
Resistance	2.51 +/-	0.1256	Ohms/sq		5.00	75.31	5.00	75.31	5.20	7.04	5.20
Film Width	0.20 +/-	0.0002	m		0.10	-2.93	-0.19	-2.93	-0.20	-0.27	-0.20
T inf	25.00 +/-	0.1500	deg C		0.60	Not Used	Not Used	0.77	0.05	1.97	1.45
T LC	35.70 +/-	0.1500	deg C		0.42	Not Used	Not Used	-0.85	-0.06	-1.98	-1.46
Emmissivity	0.85 +/-	0.1500			17.65	Not Used	Not Used	-10.16	-0.70	-0.95	-0.70
Conduction	0.00 +/-	0.0000	W/m^2		0.00	Not Used	Not Used	0.00	0.00	0.00	0.00
S-B Const	5.67E-08	W/(m^2*K^4)									
q" =	1506.219 +/-	75.428	W/m^2		5.01 % Uncertainty						
qc" =	1448.624 +/-	76.118	W/m^2		5.25 % Uncertainty						
h =	135.385 +/-	7.641	W/(m^2*K)		5.64 % Uncertainty						
					% Uncertainty	q" Uncertainty	% q" Uncertainty	qc" Uncertainty	% qc" Uncertainty	h Uncertainty	% h Uncertainty
Current	2.00 +/-	0.0050	Amps		0.25	1.20	0.50	1.20	0.66	0.11	0.66
Resistance	2.51 +/-	0.1256	Ohms/sq		5.00	12.05	5.00	12.05	6.57	1.13	6.57
Film Width	0.20 +/-	0.0002	m		0.10	-0.47	-0.19	-0.47	-0.26	-0.04	-0.26
T inf	25.00 +/-	0.1500	deg C		0.60	Not Used	Not Used	0.77	0.42	0.31	1.82
T LC	35.70 +/-	0.1500	deg C		0.42	Not Used	Not Used	-0.85	-0.46	-0.32	-1.87
Emmissivity	0.85 +/-	0.1500			17.65	Not Used	Not Used	-10.16	-5.54	-0.95	-5.54
Conduction	0.00 +/-	0.0000	W/m^2		0.00	Not Used	Not Used	0.00	0.00	0.00	0.00
S-B Const	5.67E-08	W/(m^2*K^4)									
q" =	240.995 +/-	12.119	W/m^2		5.03 % Uncertainty						
qc" =	183.400 +/-	15.858	W/m^2		8.65 % Uncertainty						
h =	17.140 +/-	1.544	W/(m^2*K)		9.01 % Uncertainty						